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THE DESIGN AND CONSTRUCTION OF SCIENTIFIC INSTRUMENTS

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I FEEL that it is a great honour to be chosen as the President of the Optical Society, especially at a period so critical to the British Optical Instrument Industry. The manner in which the Industry met the demand thrown upon it during the war is now a matter of history. Instruments of the most complicated character were made in large numbers and in a manner which before the war, or even in the early years of the war, would have been considered impossible. Under the inspiring influence of Prof. Cheshire and the late Mr Esslemont, instruments were made by firms which had never made such things before, and firms which were small makers before the war became large manufacturers of scientific instruments.

The position is now a serious one. The war increased enormously the output of instruments in this country, but at the same time it increased the productive capacity of our competitors, so that the Industry is now face to face with a keener competition than before the war. One or two British firms have always held their position against any competition, their products being almost unique both from the scientific and the practical point of view. Even these firms will soon have to face a new handicap to their sales. At the present time American Colleges have the privilege of importing scientific instruments duty-free, but in the revised tariff which will probably be introduced as soon as the new Government comes into power, the duty-free privileges will be withdrawn and the American professor will have to pay a duty of 40 per cent. on his imported instruments. The seriousness of this tax will be realised when the large purchasing power of the American Colleges is considered. America always has liked to buy good instruments and has thus been a good field for specialities. It is easy, however, to exaggerate the effect of a tax

of this kind. In the long run the well-designed and well-made special instrument will surmount any tariff wall and it is the man living inside the wall who suffers by having to pay more, or to make shift with a tool that is not so well suited to his work. The American professor knows this, but believing that it is essential to the welfare of the United States that the Scientific Instrument Industry should be a strong one, he is prepared to waive his privileges and to accept the duty. The competition in this country from European instruments bids fair to be very severe, assisted as it is by the low rate of exchange and the largely increased power of production. The result is that the British Optical Instrument Manufacturers are faced with a position which is so serious for the industry that it is almost impossible to exaggerate it. Much as I should like to dwell upon a subject so full of interest to the members of this Society and still more to be able to suggest some solution of an apparently unsolvable problem, I feel that it is a question for the politician rather than for the instrument maker. I should, however, like to express my firm conviction that the well-made British instrument will hold its own when more normal conditions of competition prevail.

The importance of scientific instruments to the community is at last being realised. The need for increased efficiency in every industrial process is resulting in a demand for scientific guidance and, therefore, for scientific instruments. One factor alone, the costliness of coal, demands economy in every direction. Economy or efficiency, for the terms are almost synonymous, can be obtained only by knowledge of the amount of waste, and this can be determined only by measurement. Measurement is the function of the scientific instrument, which in the phraseology of the dictionary is "the means by which something is effected," in many cases the "something" being a great economy.

Scientific instruments may be divided into two classes: (1) a piece of apparatus designed for the purpose of an experiment, or (2) a tool. In nearly every case the tool has been developed from the purely scientific instrument. In the words of Maxwell*, "Everything which is required in order to make an experiment is called Apparatus. A piece of apparatus constructed specially for the performance of experiments is called an Instrument." He then goes on to state that "the fundamental principle is, that the construction of the instrument should be adapted to the use that is to be made of it, and, in particular, that the parts intended to be fixed should not be liable to become displaced; that those which ought to be moveable should not stick fast; that parts which have to be observed should not be covered up or kept in the dark; and that pieces intended to have a definite form should not be disfigured by warping, straining or wearing." This all entails an intimate knowledge of the requirements of the experiment by the instrument maker, and he may well be overwhelmed with the immensity of the knowledge required when he considers the wide range of modern science. Not only is knowledge of the sciences required, but a knowledge of tools, materials, processes, and last, but not least, of men. Instrument making, like other engineering work, can

* See Handbook of the Special Loan Collection of Scientific Apparatus in 1876. Introduction by Clerk Maxwell.

only be carried out successfully in well-managed workshops, and this entails knowledge not only of the work but of the worker.

An instrument is required for a special problem. How is it to be made? What is the procedure to be adopted? First of all the designer must understand the problem. If he cannot grasp all the theory behind it, he should at any rate understand the main principles and rely for the theoretical part on someone better qualified than himself. Next, the following questions will arise:

(1) What accuracy is required?

(2) What sensitivity is wanted?

(3) What amount of money may be spent on the instrument?

The three questions are closely interlocked; indeed (1) and (2) are almost inseparable from (3). With modern high costs the majority of instruments have to be compromises, some accuracy or sensitivity being sacrificed to the heavy cost of production. Assuming that the questions have been answered, the problem is to design an instrument of a certain accuracy, having a certain sensitivity, for a certain price.

The quality of giving consistently accurate results is the prime characteristic of a good instrument, the accuracy requirements being broadly as follows:

(*a*) An instrument must have the required accuracy.

(*b*) It must have a constant accuracy.

(*c*) Every important source of inaccuracy should be known.

(*d*) Any error should, as far as possible, be capable of elimination by adjustment.

(*e*) This adjustment should be possible without the addition of other special apparatus.

(*f*) When an error cannot be eliminated it should be as constant as possible.

(*g*) When an error cannot be eliminated it should be capable of measurement by the instrument itself without external apparatus, so that the results may be corrected*.

Before analysing any particular problem in design it may be useful to consider how measurements are made. They are to be made by a human brain and that has no accurate quantitative power. For example, it can tell if an object is in front of or behind another, but it cannot state accurately the distance separating the two. With exercise the senses become extraordinarily acute, as in the case of the trained musician, but even here accuracy, regarded scientifically, is impossible†. The only power that we possess that is accurate is that of judging coincidence, or rather non-coincidence. In the case of the eye it becomes extremely accurate, the judgment of

* I must at once state my deep indebtedness to Sir Horace Darwin and Mr C. C. Mason who have allowed me to use freely the manuscript which they have prepared on "The Design of Scientific Instruments" for the forthcoming *Dictionary of Applied Physics* to be published by Messrs Macmillan & Co. I have had the privilege of working with Sir Horace for many years, and it is from him, that master of geometric design, that I have absorbed many of the ideas put forward in this paper.

† In this connection it is interesting to note that it has been found advisable to have no magnification, or practically no magnification, at the lowest power of the submarine periscope. The trained eye has developed a power for judging the distance of objects, and forms a useful range-finder. If the objects are magnified, then the power of judging their distance from the submarine is largely destroyed.

the coincidence of two bodies in a telescope, for example, being capable of a high degree of precision. The other senses are not capable of such high accuracy as the eye, although coincidences may be judged by touch and by the ear to a surprising degree of accuracy, as the limit gauge and the microphone detector show. In practice it will be found that the majority of accurate measurements depend on the coincidence of two phenomena observed by the eye. It is, therefore, one of the functions of the instrument maker to arrange that, whatever may be the quality to be measured, the final measurement depends on the coincidence of two phenomena.

Further consideration will show that it is nearly always by balancing two forces, mechanical, electrical, or magnetic, that the coincidence is obtained, that is to say, by a null method. In weighing, an index on the balance arm is observed and the weights in the pan adjusted until the index agrees with the centre line of the scale, thus showing that the weights equal the weight of the body that is being weighed. This may be taken as a typical example of the null method. Similarly in most electrical measurements the aim of the observer is to balance finally a known electrical or mechanical force against the unknown one. It is then possible by the work of previous observers to interpret the result obtained in the units of mass, length or time. The null method is not infrequently a slow one and for this reason many devices have been introduced to save time, such as the spring balance, the vernier, the divided scale, the micrometer head, etc. These are finally all null methods, as the scales, etc. have been calibrated against other weights or scales which have involved null methods. It will be noticed, however, that all measurements taken by these aids are dependent on coincidence, generally of a pointer or line and the divisions on a scale.

An instrument is required for the performance of a certain experiment. After careful consideration of all the various phenomena or chain of phenomena arising from the experiment, the experimenter decides which he will measure and from which he will deduce the information required. He then proceeds to consider the design of the instrument, bearing in mind the three considerations of accuracy, sensitivity, and cost. The accuracy of any instrument depends upon the accuracy of each individual step in its performance. Thought must be given as to which errors will be inherent to the instrument—such as the errors in the dividing of a divided circle—and to those which may be eliminated by suitable precautions. This entails, therefore, a careful consideration of the amount of any likely error in the design of the instrument. A neglect of this preliminary consideration has caused the waste of a great deal of money. Elaborate levels have been used in surveying when the greater part of the high accuracy obtainable has been sacrificed by the comparative inaccuracy of the surveying staves. In many cases instruments depending for their accuracy on the horizontality of a certain part have failed because the bubble tube provided is not capable of the accuracy required.

Similar consideration of the errors must be made in the case of electrical measurements, and frequently it is more difficult to do so than in the case of the mechanical instruments. The effect of temperature on certain resistances, thermal effects, stray magnetic fields, etc. must all be considered. If the errors can be

approximated—and in some cases this may be a comparatively rough guess—it will be seen how best to apportion unavoidable errors so that the total error may be a minimum. The time devoted to these preliminary considerations is well spent, as nothing will help to reduce the cost of manufacture so much as the knowledge that it is unnecessary to reduce a certain error below a given value because another unavoidable error will have a much greater effect in the final result. Frequently the result of increasing sensitivity is to reduce accuracy, and the usefulness of the instrument is thereby diminished. The sensitivity of an instrument may be defined as the power of detecting and measuring small changes in the property under investigation, and accuracy as the power of measuring the changes correctly. An instrument is in nearly every case a magnifying device and magnification is obtained in a variety of ways, optically, mechanically, and electrically. It is, therefore, imperative when considering the magnifying device that is to be employed to see that, when pushing the magnification to its utmost limit, some uncertainty, or the risk of an uncertainty, is not being introduced into the observation.

As in nearly all scientific work an intimate knowledge of what has previously been done is a great help in advancing a subject, so knowledge of what instruments have been already made for the performance of a particular type of experiment is of great assistance. A study of earlier instruments may frequently warn the constructor of difficulties to be avoided and may yield the clue as to the best method of attacking the problem.

The function of almost every instrument is to magnify either a movement or the distance through which something has moved. In almost every case the movements to be measured are small and therefore any errors introduced into the measuring mechanism through strain may be great as compared with the movements it is desired to measure. Strains may be set up owing to three prime causes; bad design of the moving parts of the instrument, unsuitability of the materials employed, and bad workmanship. The latter two causes are partly included in the first as the selection of the materials is clearly part of the design and good design will often minimize the effect of bad workmanship. The converse is not true—good workmanship can never annul bad design although it may go a long way towards doing so. I am afraid that in the past not nearly sufficient thought has been given to the design of instruments, especially in some of those connected with the Services, where often their development has been more or less haphazard. In some cases the rudiments of parts which have disappeared are still to be found embodied in the castings or elsewhere. A striking example of this is a particular telemeter of which a large number was made during the war. In the first model of the type a scale drum and micrometer screw connected with an elaborate differential screw with a feather and key-way were taken from another instrument and incorporated in the design, the function of the differential screw being to increase the movement of the drum relative to that of the screw and thus to obtain a more open scale. When the question of manufacturing these instruments in quantity arose it was seen that by slightly increasing the diameter of the drum it was possible to obtain the same openness of scale and at the same time to eliminate

the differential screw and its attachments. This alteration would have improved and simplified the instrument and would have materially reduced the cost of manufacture. This is a question which is closely interlocked with the question of making instruments commercially or the manufacture of scientific instruments as distinct from scientific instrument making, and one which I shall hope to discuss in more detail later.

Every possible way in which a particle can move may be resolved along three axes at right angles to each other. When, therefore, its motion is unrestricted it is said to have three degrees of freedom; in other words, three independent directions of translation perpendicular to each other. In the case of an unconstrained rigid body we have six degrees of freedom, for in addition to the three independent translations of the particle, the extended body is capable of three independent rotations about the mutually perpendicular axes. Hence a rigid body is said to have six degrees of freedom. Clerk Maxwell defined a rigid body as "one whose form does not vary," and, continuing, stated that "if a solid piece is constrained in more than six ways it will be subject to internal stress and will become strained or distorted, and this in a manner, which, without the most exact micro-metrical measurements, it would be impossible to specify."

Consider first of all the simplest case, the placing of an instrument standing on three legs in a definite position on a table. The very act of placing the instrument on the table reduces its degrees of freedom to three. It has lost one translation (the vertical) and two rotations as it now can only rotate on a vertical axis, viz., the axis perpendicular to the plane of the table. If then, one leg of the instrument is fixed, the instrument cannot be moved in a horizontal plane and it has lost its two remaining translations and has, therefore, one degree of freedom left, viz., the rotation round the vertical axis passing through the leg that is fixed. If a second leg is fixed, then the instrument has lost its last degree of freedom and is fixed. Lord Kelvin developed the method outlined above as a support for instruments, the arrangement being generally referred to as the hole, slot and plane. One leg of the instrument rests in a conical hole and as explained above loses all its translations. If a second leg rests in a V-slot or groove pointing towards the hole the instrument loses two of its rotations and finally, if the third leg rests on a plane surface it loses its third rotation. This method does not give as much stability as the well-known method of forming on the fixed base three V-grooves whose sides are inclined 90° to each other, and whose directions meet in a point at angles of 120°, and for this reason the older method is still preferred for positions where comparatively heavy instruments are used*. The hole, slot and plane is, however, employed in many mechanisms, and some examples of these will be discussed.

As a rigid body has six degrees of freedom it is obvious that if there is to be a certain relative movement between two parts, and this movement corresponds to one degree of freedom, there must be a constraint between the two pieces at five points. For example, we may take as a geometric slide the case illustrated in Fig. 1. Here two V's are formed on the under side of the upper body *A*, rounded

* Mr C. V. Boys, in his geometric stands has made a striking use of the three-groove device.

studs being mounted on them. The studs *S*, rest on the surface of the cylinder *C*. Each V touches the cylinder at two points, and, therefore, the only motions left to the body are (1) a translation parallel to the axis of the cylinder; and (2) a rotation about the axis of the cylinder. If this rotation is prevented by the point *P* being kept pressing on a plane *F* parallel to the axis of the cylinder, the only motion possible is a translation parallel to the axis. The advantages of this form of slide are great. The contact points of the upper piece are five fixed points; while the contact points on the second describe five parallel straight lines on its surface. The correct shape can be given to the first piece cheaply as no accurate machining of large surfaces is required. The second piece must have accuracy of form, but in most cases this can be obtained by using an accurate machine. For example, in the case illustrated, four of the straight lines are the generators of a cylinder and an accurate cylinder can be produced on a grinding machine at low cost. Where large forces are coming into play it will be necessary to increase the area of the surface of contact between the two parts.

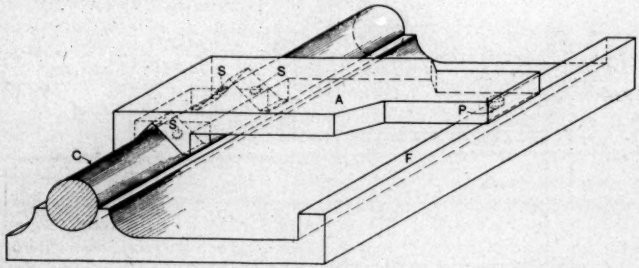


Fig. 1

Another great advantage of geometric design is that it greatly reduces internal strains in the parts. On referring again to our example in Fig. 1, it is obvious that the fact that the point *P* is free to move at right angles to the axis of the cylinder must free the slide from strain. It is essential to complete the restraints by ensuring that the two pieces remain in contact at the requisite number of points. This is frequently done by gravity, as in Fig. 1, but in a great many instruments the forces are small and the constraints are given by springs. A great deal of the success of an instrument may depend on the form of spring used and frequently sufficient care has not been taken in selecting the best type or form of spring for a particular purpose. If the two parts are stiff and rigid then one spring may be used, but as a rule it is better design to increase the number of springs and to reduce the stresses on the parts. For accuracy the spring should be under a fairly constant tension and this may be obtained by working the spring under a big extension as compared with the change in extension due to its working range. As the subject is of such importance it may be of service to illustrate a few examples of the applications of

springs, although one or two of them are not strictly connected with questions of geometrical design.

Fig. 2 is an illustration of a long spring kept under an initial tension and extended a comparatively small amount during the relative movement of the two parts to which it is attached. The instrument consists of a microscope which is to have a horizontal movement. The microscope tube is held by a fitting carried on a steel tube *A* sliding in V's and by means of the helical spring *S* the end of the tube *B* is kept in contact with the point of the micrometer screw *M*, the readings being taken on the scale *P* and the micrometer head *N*. It will be noticed that the point of the micrometer screw is not in immediate contact with the end of the tube *B*. An intermediary is employed, consisting of a steel wire *W* with hardened points bearing in conical holes in the tube and the screw, the wire being held between

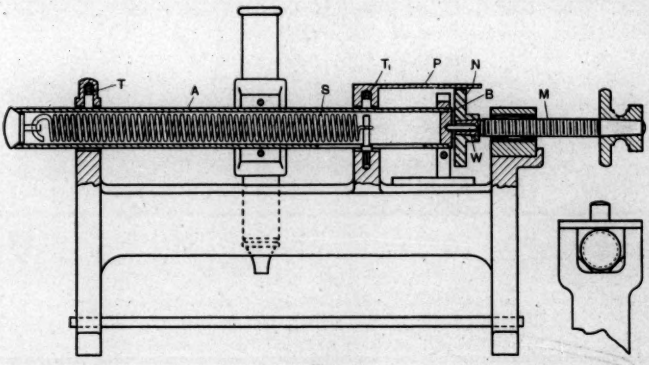


Fig. 2

them. This link prevents any want of alignment between the axis of the micrometer screw and the tube from introducing a strain on the tube or screw. The more usual but less satisfactory method is to have the rounded point of the screw bearing against a hardened flat steel face on the moving part. As the forces between these rubbing surfaces may be great the friction between them may cause a considerable force acting at right angles to the direction of movement. It is the elimination of this force that causes the improvement in the action with the pointed wire connecting link.

Fig. 3 is a good example of one spring being used to control two movements at right angles to each other. The plates *A* and A_1 are two plates forming the slits of a spectroscope and slide on a ground surface. They are pulled by means of the springs *S* and S_1 against the slides *P* and P_1 and the end of the micrometer screw *M*. It is obvious that as the screw is lowered or raised so the slit will be opened

or closed, both jaws of the slit moving an equal amount and remaining parallel to each other.

The application to instrument design of the *C* spring shown in Fig. 4 is due to Sir Horace Darwin. It enables a powerful spring to be employed in a confined space under constant load and when mounted as shown holds the piece *AB*, which

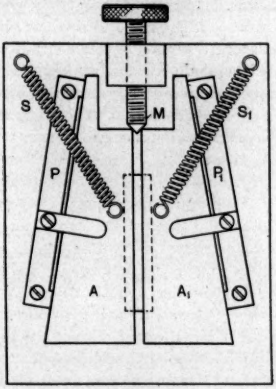


Fig. 3

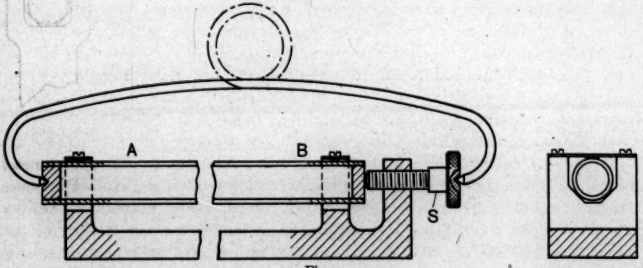


Fig. 4

is free to slide in V's, continuously against the end of the screw. If desired, a longer spring can be introduced by putting in the loop shown by the dotted lines. This method of holding two pieces together is extremely effective when two pieces are simply to be held together, no extension of the spring being required. The force exerted by the spring may be considerable and yet it is always constant. The method has the disadvantage that in a case such as that illustrated the spring does not eliminate backlash.

In instrument work, and especially in electrical instruments, the spiral spring is of great service. The problem of the control spring, as the spiral becomes in the majority of moving pointer instruments, is one of the most difficult in the manufacture of some electrical instruments. The ratios of the length of the spring to its width and thickness and also the quality of the material of which it is made are all questions which have to be seriously considered when designing a sensitive instrument*. It is a subject in which there is room for further research.

In practice there are several types of design which may be called semi-geometric, line bearings being used where only a point bearing is required by theory. A line bearing will support a much greater pressure than a point bearing, although much less than if the bearing surface were larger. Surveying and astronomical instruments are supported by geometrical bearings consisting of cylindrical trunnions resting on two parallel Y supports. If the instrument is very light these supports may be rounded so as to give contacts at four points with the two trunnions. In heavier instruments each Y piece will be formed of two planes and, assuming the two trunnions are of the same diameter, the two parallel planes in each Y must be in the same plane to secure proper line contact.

By geometric design it is generally easy to avoid backlash between the different parts of an instrument. If a cylindrical rod is turning in a cylindrical hole and the rod is too small for the hole, there will be shake between the rod and hole. If, however, as in the case of Fig. 2—a case very similar to the theodolite—the rod is held down into the Y supports by suitable springs (shown in section at T and T_1), although the trunnions and the Y supports may gradually wear with use, yet there can never be shake in the movement. Maxwell† states that, "When an instrument is intended to stand in a definite position on a fixed base it must have six bearings, so arranged that if one of the bearings was removed the direction in which the corresponding point of the instrument would be left free to move by other bearings must be as nearly as possible normal to the tangent plane at the bearing." If this principle is observed the pressure and, therefore, the friction at each bearing will be kept at a minimum and the springs required to avoid shake and backlash reduced to the minimum strength consistent with the work required of them.

A consideration of some form of geometric mountings in general use may, perhaps, make some of the points mentioned clearer, and at the same time show the great advantages of this form of design. If one piece of mechanism is to be moved relatively to another in a horizontal plane, and if the part to be moved is light, then Fig. 5 shows a simple arrangement. The cylindrical rod C can be ground without difficulty. The surface P on which the stud T preventing the rotation of the rod slides can also be ground. The four studs on which the cylinder rests can be adjusted to ensure that the movement of the axis of the cylinder is parallel to the plane of the surface P. This can all be done with the minimum amount of workmanship. (It is assumed that gravity is sufficient to hold the stud T on the ground surface; if such is not the case, a spring must be employed.) If the load

* See *Industrial Electrical Measuring Instruments*, by Kenelm Edgcumbe, 2nd Ed., p. 30.
† *Ibid.* p. 4.

on the moving part is too great then the studs may be discarded and the load carried directly on the V's. The example is of service in emphasising the importance of considering alternative ways of carrying out any desired movement or construction. In Fig. 1 the cylindrical rod is at rest and the carriage moves, in Fig. 5 the positions are reversed. Each case must be dealt with on its merits after a consideration of the weights to be moved, distances to be traversed, and the amount of probable wear.

In the case of a vertical slide, such as a cathetometer, the conditions are different and the design of the spring requires serious consideration. Fig. 6 is an example of the mounting for a telescope to be capable of movement on a vertical slide. The telescope, which is not shown in the figure, is carried on a tubular carriage on which four screws are mounted, the supporting rod R being gripped between them by the point P pushed by the flat spring F against the rod. The weight of the carriage is supported by the screw S, which is held in place by its nut which is

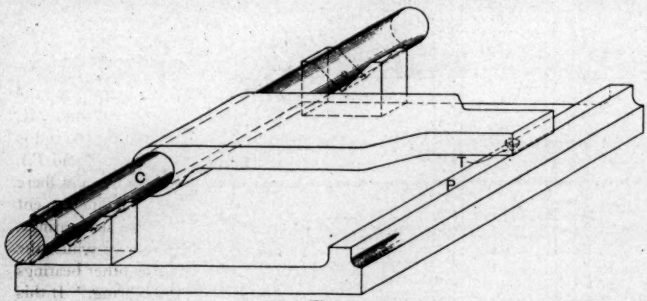


Fig. 5

clamped to the rod. Assuming that the gravity control is more than sufficient, the only degree of freedom left is in the horizontal plane. In the particular case under consideration this was not of importance. The illustration does, however, bring out one of the great advantages of geometric design, namely, that the point forming one of the supports or controls in the design can be adjustable so as to give the relative motion of the fixed and movable parts. In this case the point of the screw S is adjustable and in a simple manner gives the vertical adjustment.

A more complicated form of slide for a cathetometer carriage is shown in Fig. 7. The long casting O is supported on a steel rod (not shown in the figure) and is machined on five of its faces. A carriage C, carrying the telescope T, is held against three of the faces at the points P by means of the three springs F, F_1 and F_2. The greater part of the weight of the carriage is balanced by a weight not shown in the figure, the remainder of the weight being taken by the plunger R. The plunger can be raised or lowered by means of the screw S mounted on the lower carriage, which can be clamped in any position by means of the screw G. It will

be noticed that the clamping or unclamping of this screw introduces no strain on the telescope carriage and that this is free to take up its position without strain.

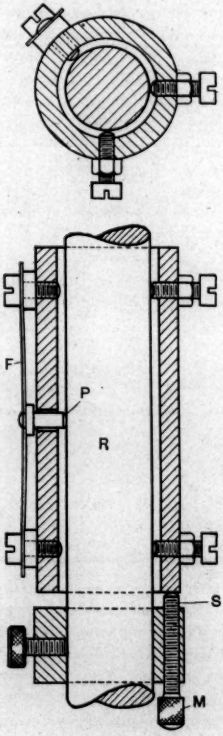


Fig. 6

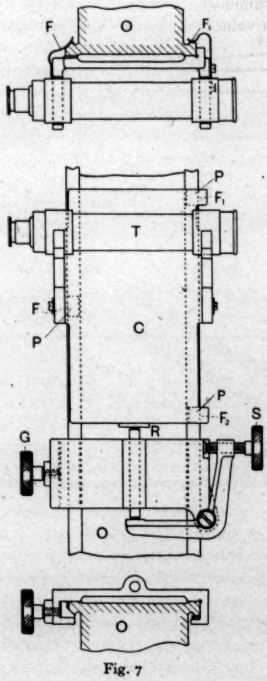


Fig. 7

A large number of examples might be given, but the above may serve to show how much design may simplify construction. The majority of mechanics know from a study of satisfactory and unsatisfactory lathe beds which designs are geometrically sound. A lathe and an instrument, such as those we have been discussing, are closely akin, except that the forces and wear on a lathe bed are

much more severe, and surfaces have to be employed instead of point or line contacts*.

The design of parts that have to rotate relatively to each other must follow the same general principles, although in some cases they may appear to wander a good deal from theory. The one serious drawback to strictly geometric design is the fact that there may be—for want of a better term—a certain amount of "floppiness," and this cannot be tolerated in many instruments—for example, in surveying instruments. In the case of small rotational movements geometric design is of great value. In the well-known rocking microtome the parts on which the section

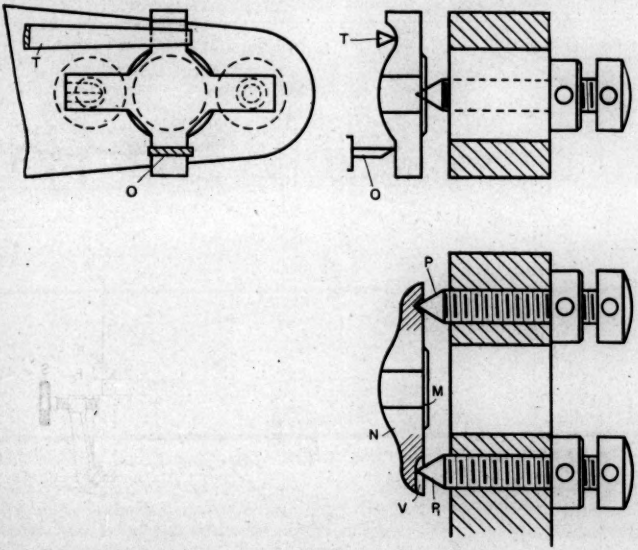


Fig. 8

is carried and which are moved forward in steps as small as ·001 mm. are blunt knife edges of cast iron. To show the efficiency of the design it may be mentioned that a microtome has been made from untooled castings put together with as little work as possible and it has cut sections as satisfactorily as a highly finished instrument. It should be stated that the screw and its attachments were correctly finished†.

* See also "The Mechanical Design of Instruments," by Walter Rosenhain. *The Proc. of the Optical Convention*, p. 31, 1905.

† See "Scientific Instruments, their Design and Use in Aeronautics," by Horace Darwin, The First Wilbur Wright Memorial Lecture. *Aëronautical Journal*, July, 1913.

In the mounting of mirrors it is important to attend to the number and position of their bearings, for any strain in the mirror spoils its definition. Geometric mounting often simplifies the attachment of the mirror to a moving part. Fig. 8 illustrates the mounting of the mirror used in an instrument in which it is necessary for the mirror to oscillate at a high frequency (3000 per sec.). The mirror M of stainless steel and 4 mm. in diam. is fixed on the mounting N which is held against the screw points P and P_1 by means of the spring T of triangular section and the knife-edge of the part O. This latter part is attached to the diaphragm of the

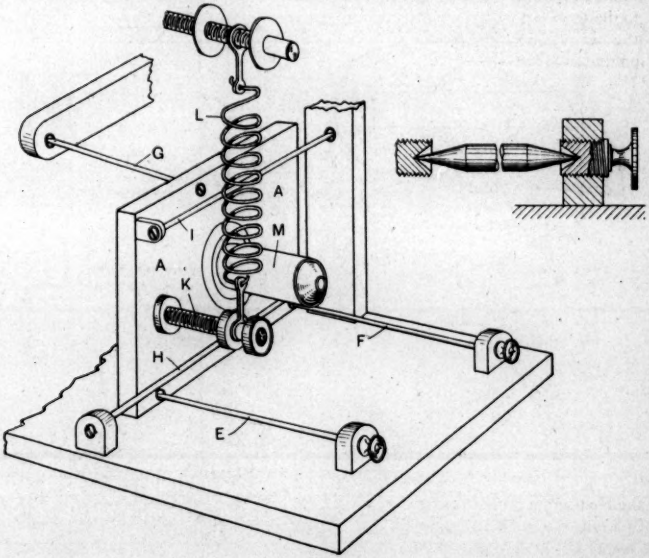


Fig. 9

instrument, the movement of which it is desired to record. The mirror rocks round the points P and P_1, which bear in a hole and slot respectively.

The Mallock vibrograph well illustrates how geometric design can simplify construction and yield results which are practically unobtainable in any other way. The instrument (Fig. 9) was designed by Mr A. Mallock for recording the vibrations set up in the buildings adjoining the Central London Railway*. The brass plate A

* Report of the Committee appointed by the Board of Trade to enquire into the vibration produced by the working of the traffic on the Central London Railway. (Memorandum by Mr A. Mallock. Appendix IX.)

is supported by the spring *L* and its movement in every direction (except in the vertical plane) is controlled by the finely pointed rods *E*, *F*, *G*, *H* and *I* (shown in detail in the small figure). The plate carries a photographic objective *M* which throws the image of a quartz fibre on to photographic paper. When vibration is experienced the camera, etc. move, but owing to the inertia of the plate and the almost entire absence of friction the objective remains stationary and the earth movements are recorded on the photographic paper.

A great deal of the success of a measuring instrument may depend on the method of mounting the screw. It is essential that no indeterminate strains should be given to the screw or nut. Many devices have been designed for this purpose. Sometimes the nut is carried in a rocking mounting so as to allow it to take up its position on the screw but not to permit any rotation. An excellent example of this is shown in

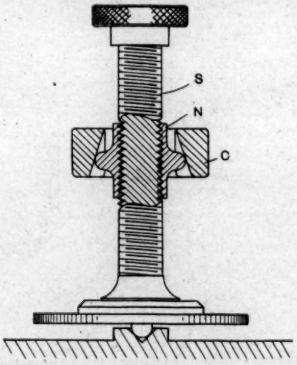


Fig. 10

the feed screw of the rocking microtome (see Fig. 10) in which the screw *S* works in a nut *N* formed in a rocking piece which rests in two V grooves in a ring-shaped casting *C*. In general practice the connecting link between the micrometer screw and the part to be moved is best made as a link (see Fig. 2), but there are many modified forms of hook-joint that are in general use.

The making of a satisfactory screw and nuts is a difficult problem, but the instrument manufacturer now knows far more about the subject than he did in 1914. The demand for instruments fitted with accurate screws entailed the manufacture of accurate screw-cutting lathes and a knowledge of screw threads which has quite revolutionised the subject. As showing the need of information on the subject attention may be drawn to the defective design of a nut forming part of a gun clinometer. Many thousands of this clinometer were made during the war and the specification for its manufacture was extremely severe. The screw, which

was about 5 inches long, was threaded throughout its length with a double-threaded screw of 0·1 inch pitch. The nut was required to pass throughout the whole length of the screw without any variation in the fit—an almost impossible task. The nut was solid but fitted with three plungers *P*, pushed against the screw by three springs *S*, which were supposed to take up any shake (see Fig. 11). After a few days' use in the field the nut began to feel loose on the screw and it was not long before the plungers became useless. The most casual consideration will show that the design of this nut is unsound and yet, although a geometrically designed nut (see Fig. 12) was submitted, it was impossible to persuade the authorities to try it. In this design the nut was cut away so that the screw would bear on part of the thread at four points, the plunger *P* holding the screws against these points. It is no

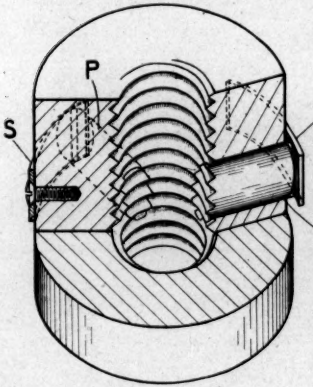


Fig. 11

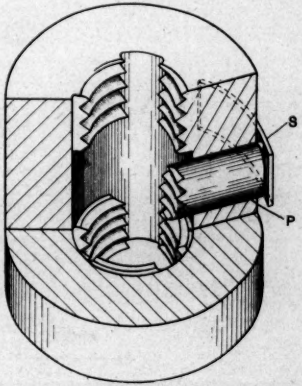


Fig. 12

exaggeration to say that, if a geometric nut had been substituted, each instrument would have cost much less and the output greatly increased. In addition a nut would have been provided that would have stood much wear and have given consistent readings over a long period of time.

Enough consideration has not always been given to the scales used in instruments and it is a point worth dwelling on, although, as a rule, the modern scale is a great improvement on those fitted to old instruments. The position of the scale or the reader by means of which the scale is read is of importance. If conveniently arranged, a good deal of time may be saved in taking a reading, and time is a weighty consideration when many readings have to be taken. If a reading is being taken with a microscope, it is often more convenient to have a low power with a comparatively large field of view than a higher power with a restricted field. The former may enable you to see the figures on the circle and at the same time

give sufficient accuracy for the purpose of the experiment. The relative length of the short and long lines on a scale is a point of some importance. As a general rule it may be stated that if the long or ten lines have a length of 1, then the fives should be 0·75, and the units 0·5. In many cases it has been the practice to make the shortest stroke of the same length as the space between it and the adjoining one, i.e., if in a theodolite circle the space between two small divisions is $\frac{1}{3}^{\circ}$ and this is equivalent to 2 mm., then the length of the stroke should be 2 mm.

It is always advisable to remember that an open scale is easier to read than a crowded one. The eye becomes remarkably proficient in sub-dividing small spaces. Mr Trotter* has given a good deal of consideration to the size of figures on instrument scales, and suggests a simple block letter, the total width of which is $\frac{7}{10}$th of the height and the thickness of the strokes forming the figure $\frac{1}{10}$th of the height, as the most satisfactory. Some experiments made at the National Physical Laboratory have shown that when the figures have to be made luminous by means of a radium compound the proportion of width of line to the height of the figure for maximum legibility should be about 1 to 8 for letter and figures in which the height exceeds 5 mm. Below this limit experience suggests that the breadth of line may be usefully increased to one-sixth of the height of the figure†.

In designing an instrument the conditions under which it is to be employed must be considered. If it is to be used in the laboratory by a skilled observer, the design may be entirely different to that which is necessary if it is to be used in the workshop by an unskilled observer. Then, again, if it is to be used out of doors it must be impervious to weather conditions and robust. This demands different construction to the laboratory instrument and yet, perhaps, not nearly so different as may appear at first sight. The research instrument of to-day is the tool of to-morrow‡. Instrument makers have, I think, failed in this, that they have not realised sufficiently quickly the new applications of research to industry. The X-ray is discovered and in a few years it is one of the means adopted for testing the flaws in materials. The number of such examples is very great.

What then does the new application of an old instrument or the use of a new one entail? First of all imagination to see that there must be a demand, or that a demand will exist in the near future. Assuming this, and believing there will be a considerable sale, the most efficient and economical methods of making it must be considered. One or two of the leading American instrument firms have organised development departments in which the instrument is developed from its laboratory form to one suitable for the workshop. The members of the development department design it with quantity production always in their minds, making perhaps a dozen instruments which are put out into service with a view to attract outside criticism—it being understood that the firm which is testing the instrument will

* "A set of proposed standard numerals for the scales of measuring instruments," by A. P. Trotter. *Proc. Inst. Elect.*, Eng., 54 (1916), 273.

† "An Investigation of Radium Luminous Compound," by C. C. Paterson, J. W. T. Walsh and W. F. Higgins. *Proc. Phys. Soc.*, Lond., 29 (1917), 232.

‡ "La machine à diviser est intéressante, le microtome des naturalistes l'est davantage; la machine à découper les tranches de saucisson l'est encore bien davantage." *Construction, description et emploi des Appareils de Mesure et d'Observation*, by H. Bouasse (Paris: Librairie Delagrave, 1917) p. ix.

have the experimental model replaced without extra charge by the final model when that has been evolved. After the criticisms are received the final model is prepared and the development department hands to the works a finished instrument for manufacture on a large scale. There are not many firms in this country which can afford a separate development department and yet the procedure must be adopted even if the department is not there.

The difference between scientific instrument making and the manufacture of scientific instruments is great. The latter means quantity production and is an engineering problem. One of the lessons the war taught is the possibility of cheap production if only the quantity to be made is sufficiently great. The greatest difficulty that faces the instrument maker is to know when he is justified in commencing to make any particular instrument in large quantities. Having decided that there is the possibility of a fairly large sale then, I believe, it is advisable to handle the matter boldly, to consider what parts may be pressed or die-cast and to incorporate as many standard parts as possible. A reduction in cost may frequently be made by replacing brass or bronze by cast iron or die-cast aluminium parts. Well-made metal patterns are essential on account of the time saved in preparing jigs and fixtures. There are now so many new finishing processes available that they must be studied before a final decision is taken. The lacquer and paint spray, the sand blast and the electro-plating plant, all form part of the equipment of a modern instrument factory and, by allowing the employment of unskilled labour, help to reduce the cost of manufacture. The moulding of ebonite and bakelite is a valuable process and will, I am convinced, be used largely in future instrument work.

I commenced my address by referring to the catholicity of knowledge required by the instrument maker. Knowledge is required not only by the leaders of the industry but by all their employees. The authorities at two or three of our Universities are widening their courses in optics to try and train the future designer of optical systems.

The formation of the Optical Engineering Department at the Imperial College of Science under the direction of Prof. Cheshire is a step which should do much to assist the manufacture of scientific instruments in this country. I hope that it may be possible so to incorporate Prof. Pollard's lectures on Mechanical Design in the work of the University that they will be regarded as bearing on scientific instrument design and manufacture in the broad sense and not limited in any way to the design of optical instruments. The British Scientific Instrument Research Association, under the able direction of Sir Herbert Jackson, promises to be a great help to the Industry. For a young Association it has done valuable work and it promises to do much more in the near future. If it is true to the aims of its founders it will always be a source of inspiration to the Industry.

I believe there is a future for the manufacture of scientific instruments in this country. Industry is beginning to appreciate the help that instruments can give to its development. The growth of science and the spread of scientific education will open out many new opportunities for the use of instruments. The instrument maker must rise to these opportunities.

A NEW OPHTHALMOSCOPE

By Prof. J. K. A. WERTHEIM SALOMONSON

(Communicated by the President)

Read and discussed, 13th January, 1921

Since the discovery of the ophthalmoscope by Helmholtz, disclosing the interior of the living human eye, many different attempts have been made to keep a permanent record of the aspect of the retina on a photographic plate. This has proved to be much more difficult than viewing the background of the eye. The greatest difficulty has been caused by the reflections from the surface of the cornea and the anterior and posterior surfaces of the lens. Different ways have been tried to get rid of these reflections and after more or less successful attempts by Bagnéris, Guilloz, Gerloff and others, Dimmer succeeded in obtaining satisfactory results. Shortly afterwards Thorner, and also Wolff, working on different lines, showed photographs of the living human retina which were nearly as good as those of Dimmer; his photographs are generally excellent. Nicolaew was also successful in obtaining good negatives of the eyes of animals, but his method did not yield satisfactory results with the human eye, the fundus of which is infinitely more difficult to photograph than the animal fundus. For practical purposes as yet only Dimmer's and perhaps Wolff's methods have to be considered, but Dimmer's method necessitates a costly instrumentarium, requiring much room and skilled assistance. I do not know of its being used outside his own clinic, except by a very few specialists (e.g. Hess).

The different methods for obtaining an image of the fundus, free from reflections, have been ably discussed by Gullstrand, who gave a clear and critical review of the general and special conditions necessary for getting clearly defined ophthalmoscopic images, free from any reflection. Finally his results were embodied in his large demonstration-ophthalmoscope, constructed by Zeiss, which shows the ophthalmoscopic appearance of the human eye with less difficulty, more extensively with a higher magnification and yet more clearly than any other instrument of the same kind. As yet this instrument cannot be used for photographic purposes, but it seemed to me that it might possibly be rendered suitable for such. After a few preliminary trials I had an instrument made for me, differing in many respects from the original one.

The Nernst lamp was discarded and was replaced by a lamp of greater intrinsic brilliancy. The arrangement of the illumination-tube was slightly changed so as to allow a relatively greater part of the light to reach the eye. A suitable small camera having been adapted to the instrument, I got, after a few failures, usable negatives of a diameter of 26 to 30 millimetres, showing about 27 degrees of the fundus and covering an area of $4\frac{1}{2}$ times the diameter of a normal optic disc. The negatives were sometimes good, though very often blurred, owing to the long

exposure of 0·4 to 0·5 of a second. I have tried to get better results in quite another way, but still using the principle of indirect ophthalmoscopy. The greatest difficulty lies in the elimination of the reflections from the ophthalmoscope lens. I have succeeded in this and constructed the photographic instrument. Before considering it, however, I shall describe another instrument, which is used solely for viewing the retina and for showing it to students as yet unskilled in the art of ophthalmoscopy (Fig. 1).

For illumination a small 25 candle-power gas-filled lamp (Fig. 2) with a straight tungsten spiral filament is used, normally burning on a 4-cell accumulator or on a small alternating current transformer for 8 volts secondary. The light intensity is generally reduced by means of a sliding contact variable resistance. A condenser projects the image of the filament on a narrow slit. A lens placed on the slit projects the condenser aperture on the ophthalmoscope lens, the light being deflected through 90 degrees by a small totally reflecting prism placed beneath the slit, so as to permit of placing the illuminating tube at a right angle to the axis of the viewing tube which contains the ophthalmoscope lens. The real image of the retina, formed by the ophthalmoscope lens, can be examined through an aperture beneath the prism. We inspect that image with a kind of short microscope, the objective of which has a focal length of 55 millimetres, the eyepiece being one of the Huygenian type as used in the ordinary microscope. The magnification is altered by using different eyepieces.

In order to eliminate the images reflected by the ophthalmoscope lens, the following arrangement is used. A small achromatic double image prism of calcite and glass is placed between the condenser and the slit, causing two images of the filament to be projected in the plane of the slit. Only one of these, formed by the ordinary rays, falls on the slit; the other falls on one of the slit plates and is arrested. Consequently the eye is illuminated with polarised light and the images reflected by the ophthalmoscope lens are also polarised. By means of a nicol prism placed in the microscope tube these reflections are extinguished. The light illuminating the retina and reflected from the fundus of the eye has become depolarised and can be observed with the microscope. As a matter of fact the retina is clearly seen without any appreciable disturbing reflections from the surfaces of the intervening media. Also the retinal reflections, which in young patients are nearly always very noticeable, seem to be very slightly lessened.

With this instrument we can see at once 27° of the fundus of an emmetrope eye, corresponding to about $4\frac{1}{2}$ diameters of the papilla nervi optici. The whole field is remarkably flat, and is sharp up to the edges. The magnification is generally about 14 diameters, or about the same as when the eye is examined with the direct method, but with an angle of view many times greater. By using stronger eyepieces the image, which is in the upright position, can be magnified up to about 50 times, the angle of view of course being somewhat reduced. As the illuminating filament can be regulated to any desired degree of brightness we can even with this high magnification get a profusion of light, and exceedingly clear and sharply defined images of the fundus.

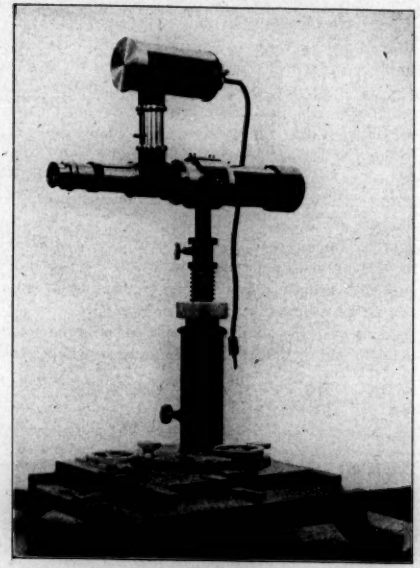


Fig 1

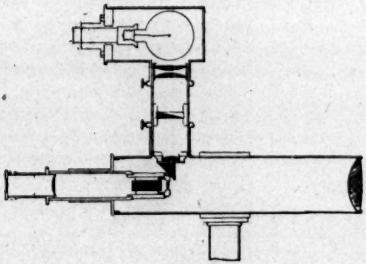


Fig. 2

When in use the distance from the patient's eye to the instrument is about 90 millimetres. The only change necessary when examining different patients is the focussing. In cases of strongly myopic, hypermetropic, or astigmatic eyes, examination is still possible with the patient wearing his own glasses.

The ophthalmoscope lens in this instrument is one of the well-known aspheric aplanatic single lenses of 43 mm. clear aperture, made by Zeiss. One might use any other aplanatic combination of lenses, provided the focal length and aperture were satisfactory. The multiple reflections from a combination of lenses would be obscured as effectually as those from a single lens.

We can now return to our photographic ophthalmoscope. This has been constructed on the same principle as the demonstration instrument, from which it differs in the following points:

(1) A photographic camera is fitted to the instrument, which is also provided with a shutter for making instantaneous exposures.

(2) The illuminating agent is a small arc lamp, running on some 5–6 amperes, instead of the incandescent electric half-watt lamp.

(3) The reflections from the ophthalmoscope lens are rendered innocuous, not by using polarised light, but by the use of small screens, as will be explained later on.

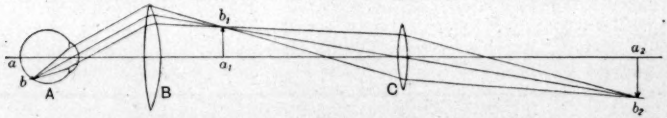


Fig. 3

The photographic apparatus contains two different optical systems—one for viewing or photographing the retina and a second one for illuminating it. The former optical system is diagrammatically represented in Fig. 3. The rays starting from a point b on the retina pass through the lens of the eye and the cornea and leave the latter as a bundle of parallel rays. These reach the ophthalmoscope lens which forms a real inverted image a_1b_1 at its back focus. An image of a_1b_1 is then formed at a_2b_2 on the photographic plate by means of the photographic lens C. The distance of the ophthalmoscope lens from the eye must be made such as to form a sharp inverted and enlarged image of the iris and eye pupil in the plane of the photographic lens C. The combination of these conditions demands that there should be a definite relation connecting the diameter of the eye pupil, the aperture of the photographic lens, the focal length of the ophthalmoscope lens, and the final magnification of the retinal image, if we wish to get the maximum of light on the plate. This condition is expressed by the formula

$$\frac{d_2}{f_2} = \frac{d}{f_1}\left(1 + \frac{1}{V_2}\right),$$

in which d_2 is the opening, f_2 the focal length of the photographic lens, d the diameter of the pupil, f_1 the focal length of the ophthalmoscope lens, and V_2 the total magnification.

Let us assume that we wish to take a photograph showing the retina with an enlargement of, say, four times. We can do this by taking a short focus ophthalmoscope lens with a low initial magnification of, say, two times, which is compensated by enlarging the image twice again with the photographic lens. But we might also have taken a longer focus ophthalmoscope lens, enlarging the retina four times, and reproducing this image on the same scale with the photographic objective. Assuming that the pupil was dilated in both cases to 8 millimetres, the formula shows that with the low primary magnification an exceedingly high aperture photographic lens of something like $f/2{\cdot}5$ would be necessary, whereas with a long focus ophthalmoscope lens an aperture of $f/4{\cdot}5$ would be sufficient for the photographic objective. In my apparatus I have therefore used the ophthalmoscope lens

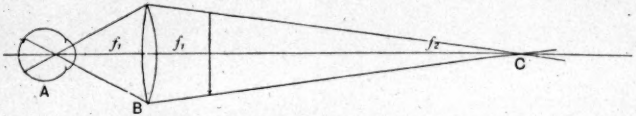


Fig. 4

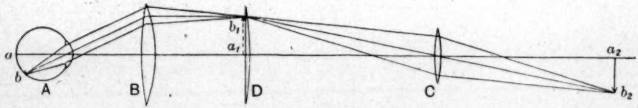


Fig. 5

with the longest focus I could get. As this lens must give aplanatic images I have taken an aplanatic aspheric ophthalmoscope lens of 7 cm. focal length and 5 cm. diameter, made by Zeiss. For my photographic lens I could take any good lens working at about $f/4{\cdot}5$, but I had still to fix on a proper focal length for the objective. This point will be best understood from a study of Fig. 4, in which *C* represents the cardinal point of the photographic objective. By taking an objective of very short focal length, we get only a small part of the image of the retina on the plate. In this respect it is a decided advantage to have as great a focal length as possible. But, on the other hand, this renders the whole apparatus unmanageable, as its dimensions become too great. I have therefore taken an objective with a focal length of 15 cm., giving an image of nearly 41 mm. out of a possible 50 mm., and covering 5·4 diameters of the optic disc. The entire length of the viewing tube is now 67 cm., to which 8 cm. must still be added for the focussing eyepiece. I might have got a larger field of view with a shorter focus photographic objective by using a field lens (*D* in Fig. 5), but I could not do this as I should have had to eliminate also the reflections from this field lens.

The illuminating system is diagrammatically represented in Fig. 6, *K* being the crater of the arc lamp, *E* the condenser, *G* a diaphragm with a lens, and *F* an aplanatic lens. An image of the crater is projected in the plane of the diaphragm

G, an image of which is projected at the end of the illuminating cone by the lens *F*. The lens at *G* is not necessary, but it serves to form an image of the surface of the condenser in the plane of the aplanatic lens *F*. A shutter is placed in front of *G*. This illuminating system, in combination with the viewing system, is shown in Fig. 7. Both systems have one point in common; the ophthalmoscopic lens *B* and the aplanatic lens *F* are one. This is made possible by inserting the totally reflecting

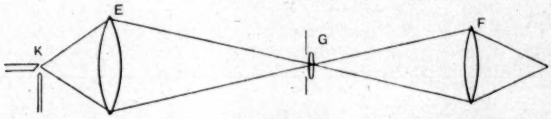


Fig. 6

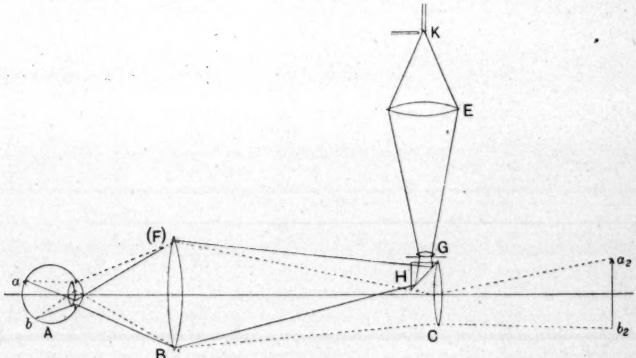


Fig. 7

prism *H* in the path of the illuminating rays, so as to place the arc lamp with the condenser perpendicular to the axis of the viewing tube.

By placing the prism *H* in front of the objective, part of this objective is not used for reproduction of the ophthalmoscopic image. As the ophthalmoscope lens reproduces the pupil of the eye in the plane of the photographic lens, we have divided the pupil into two parts, one part transmitting the illuminating rays and the other part transmitting the rays from the retina to the photographic plate. In my apparatus these parts are arranged as shown in Fig. 8 *a*, where *rs* is the section of the narrowest part of the bundle of illuminating rays, *tu* being the section of the bundle of visual rays which start from the retina and reach the objective. Assuming for the pupil a diameter of 8 mm., for the section of the illuminating cone 2 mm., and leaving 2 mm. clear space between the illuminating and image

forming rays, we get only 0·162 of the theoretically obtainable luminosity in a case where exactly one-half of the surface of the pupil is used for passing each of the two light cones. We might have got a better economy by using divisions of the surface of the pupil as shown in the next figures, the economy factor being only 0·109 in Fig. 8 *b*, but growing to 0·391 in Fig. 8 *c* and 0·468 in Fig. 8 *d*. I have not used these economically better forms as they would have caused some trouble with the construction. Also there is some advantage in using the best part of the eye for photographic purposes, which would not have been possible with an arrangement such as the one shown in Fig. 8 *d*.

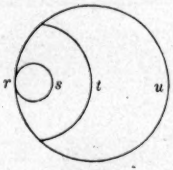


Fig 8*a*

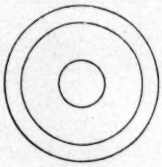


Fig. 8*b*

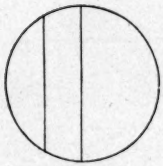


Fig. 8*c*

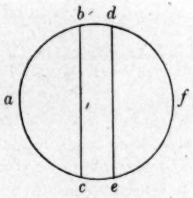


Fig. 8*d*

We must now turn our attention to the reflections from the surfaces of the different lenses. The reflections from the cornea and the eye lens have already been eliminated by our arrangement of the illuminating and the reproducing cones of light. From a consideration of Fig. 7 we find that, if only the clear space of about 2 mm. between the cones be preserved, no illuminated part of the cornea or the eye lens can be seen by the photographic objective. But this means that no reflection from the cornea or the eye lens disturbs the reproduction of the retinal image.

The reflections from the ophthalmoscope lens must be eliminated. In the scheme reproduced in Fig. 9, where *A* represents the eye, *C* the photographic lens, and *B* the ophthalmoscope lens, the reflections from which are formed at *c* and *d*, we get the first retinal image at a_1b_1. The photographic lens gives a sharp reproduction of a_1b_1 on the plate at a_2b_2, whereas the reflections are sharply reproduced

at c_1 and d_1. On the plate they would show, as crescent-shaped spots, the form of the transparent part of the photographic lens. We can eliminate these reflections by causing them to fall on very small screens placed at c_1 and d_1. These screens, with diameters of about 1 and 2 millimetres, are mounted either on a glass plate or on a pair of very fine wires, and can be carefully centered. But when this has been done we discover that a small quantity of light is diffracted round the small screens. In order to minimise the effect of this diffracted light, I placed a small screen on the condenser *E*. This was reproduced on the lens *B* by means of the small lens *G* (Fig. 7). The place and dimension of this last screen were carefully calculated so that its image just covered the part of the lens from which the reflections took place. By taking a lens *G* of slightly larger focal length than necessary I prevented this last screen from causing a gap in the final picture. Furthermore, I do not use an absolutely opaque screen, but a yellow transparent one, which does not hamper the illumination of the retina and yet greatly diminishes the action of the diffracted rays on the plate.

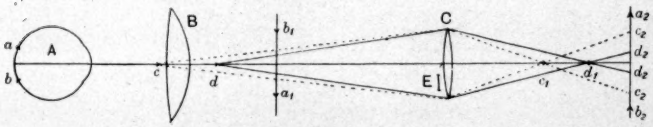


Fig. 9

As yet I have not mentioned a third reflected image which is formed by double reflection from the ophthalmoscope lens. This image is visible as a very thin light line in the form of an exceedingly narrow crescent. It has the peculiarity of being completely polarised perpendicular to its direction. The intensity is so slight that there is no need to consider this reflection. We can just see it on most negatives, but it does not cause any trouble.

There are still a few points which must be mentioned. In my instrument an arc lamp using about 5–6 amperes is employed. Would it perhaps be advantageous to use a heavier current? The answer is that this should not be the case, at least if we have the right to assume that the intrinsic luminosities of 5 and 25 ampere arc lamps are the same. Now I am willing to admit that there may perhaps be a very slight difference, but I am not quite convinced of it. We can easily prove that we cannot get more light with any modified form of illuminating lens system.

Before photographing we must first focus the image. We can do this only if the intensity of the light has been much reduced, for the patient would not be able to suffer the prolonged action of so strong a light. I have overcome this difficulty in a very simple way. The instantaneous shutter, with which the instrument is fitted, is placed in front of the prism in the illuminating tube. When in the position of being set the shutter presents an opening covered with a smoked and varnished mica plate, through which enough light passes to enable us to examine carefully

the fundus of the eye and focus the image. A ground glass is not needed; the image is directly viewed with a magnifying glass, magnifying $3\frac{1}{2}$ times and showing the whole image of 40 mm. diameter at once. As soon as the focussing seems to be satisfactory, the magnifying glass is slid sideways and an already opened plate-holder is brought in its place. At the same moment the shutter is released and a plate is exposed.

The exposures can be varied from $\frac{1}{20}$–$\frac{1}{5}$ second—generally $\frac{1}{10}$ or $\frac{1}{12}$ of a second exposures are used. With good panchromatic plates we usually get fully exposed negatives. Of course there is a slight loss of light at the peripheral parts of the

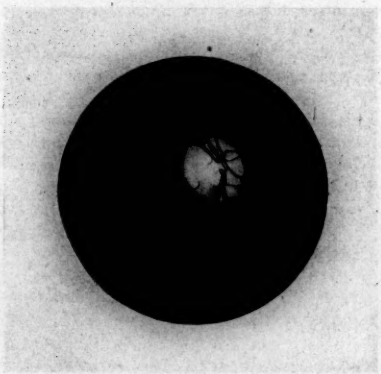


Fig. 10

negative, the central parts being more strongly exposed. I do not think that this can be remedied in any effectual way, yet with some care pretty good prints may be got from the negatives.

The diameter of the negatives is about 40 millimetres. They are mostly sharp enough to stand a magnification of two to three times. Fig. 10 is a reproduction from a negative showing a normal eye.

The apparatus can be used for both eyes without any alteration except the ordinary focussing. The whole instrument is mounted on a stand which allows of careful adjustment in three directions. Its use is not any more difficult than the making of an ordinary photograph with a stand camera.

DISCUSSION

Mr J. Pizzala asked if all the photographs exhibited were of eyes treated with atropin, and whether it was necessary to use atropin for direct ophthalmoscopy.

Professor Cheshire said that some years ago Prof. von Rohr had told him that Prof. Gullstrand had discovered that the zone of the pupil with a radius of 4 mm. was free from spherical aberration. He thought that this might possibly explain the extraordinarily good definition the author had obtained with his instrument.

Mr F. Whitehead asked if any special process had been adopted in sensitising the photographic plates to render them panchromatic or sensitive to the red, and if a colour screen or filter had been employed.

The author, in reply, said the eye under test was always dilated, by means of atropin, to at least 7 mm. aperture. He did not, however, use atropin unless when taking photographs.

The photographic plates employed were panchromatic, mostly of German make ("Agfa" brand), but similar results had been obtained with English panchromatic plates. None had been specially treated before using and all makes had been used without any screen or filter.

A NEW ANASTIGMATIC FLAT FIELD TELESCOPE AND ITS APPLICATION TO PRISMATIC BINOCULARS

By H. DENNIS TAYLOR

Read and discussed, 13th January, 1921

The public have become so accustomed to the usual prismatic binocular consisting of an achromatic objective, two inverting prisms, and a Kellner eyepiece that they have come to regard them as incapable of being improved upon. While there is no doubt that the best types of such instruments are by no means to be despised as regards their optical performance, yet those who are more versed in optical science than the man in the street are well aware that all telescopes are characterised by certain alternative defects which cannot possibly be got rid of, provided that present principles of construction are adhered to. In the same way, up to the year 1895 or so, it was thought by the average photographer that the lenses used by him were as perfect as it was possible to get them, as in fact they were so long as the old principles of construction were adhered to.

It was only later that it was fully realised by the photographer what a great improvement in the optical performance and rapidity of the lenses that he used could be attained by a radical departure from the old principles of construction, which consisted in the use of one or more compound achromatic lenses through which the oblique pencils were constrained to pass excentrically by means of a suitably placed stop. Now it had long previously been demonstrated by Petzval that if by the use of excentricity corrections, due to such excentric passage of oblique pencils, the astigmatism generally characterising oblique pencils is neutralised, leading to a curved but anastigmatic image, then the radius R of such image is expressed by the simple formula $\frac{1}{R} = \frac{1}{fn}$ in the case of a simple lens of refractive index n and principal focal length f. In the case then of a simple positive lens of refractive index 1·5 the radius of curvature R of an anastigmatic image yielded by it is $1{\cdot}5f$, and if the refractive index is 1·625 then $R = 1{\cdot}625f$, so that a positive lens of high refractive index has an advantage as regards flatness of field over one of the same focus but of low index. Further, in the case of compound lenses, he demonstrated that the radius of the anastigmatic image the system is capable of is expressed by the formula

$$\frac{1}{R} = \frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \ldots.$$

Let us now consider the usual forms of double compound lenses consisting of a positive lens of one refractive index together with a negative lens of lower power

but higher refractive index and higher dispersive power. Let D be the ratio of the principal focal lengths of the two lenses which generally is the ratio between the dispersive powers of the two glasses. Let f be the principal focal length of the positive lens and F that of the two combined then $\frac{1}{F} = \frac{D-1}{D}\frac{1}{f}$ and conversely

$$\frac{1}{f} = \frac{1}{F}\left(\frac{D}{D-1}\right) \quad \text{and} \quad f = F\frac{D-1}{D}.$$

Thus, if n be the refractive index of the positive lens and m that of the negative lens, the curvature radius of the anastigmatic image is given by

$$\frac{1}{R} = \frac{1}{fn} - \frac{1}{Dfm} = \frac{Dm-n}{fDnm},$$

in which for f we may substitute

$$F\left(\frac{D-1}{D}\right),$$

thus obtaining

$$\frac{1}{R} = \frac{Dm-n}{F(D-1)nm}.$$

If we assume $D = \frac{8}{5}$ and $n = 1{\cdot}5$ and $m = 1{\cdot}625$, then we get

$$\frac{1}{R} = \frac{\frac{8}{5}(1{\cdot}625) - 1{\cdot}5}{F\left(\frac{3}{5}\right)(2{\cdot}4375)} = \frac{1{\cdot}208}{F(1{\cdot}625)} = \frac{1}{F(1{\cdot}345)}.$$

But if the lens were a simple one of refractive index $= 1{\cdot}5$ and principal focal length F then $\frac{1}{R}$ would be $\frac{1}{F(1{\cdot}5)}$. Therefore as long as we are obliged to use negative lenses of glass of higher refractive index than the glass used for the positive lenses, in order to get correction against spherical aberration, especially in the case of cemented doublets, we are handicapping ourselves when trying to obtain anastigmatic images that shall approach to the condition of flatness. It was the realisation of this fact which prompted Schroeder to bring out his photographic lens (known as the Concentric) whose lenses were composed of a positive of focal length $1{\cdot}5$ combined with a negative of focal length minus $1{\cdot}6$ while their refractive indices were $1{\cdot}6$ and $1{\cdot}5$ respectively so that here we had

$$\frac{1}{R} = \frac{1}{1{\cdot}5\,(1{\cdot}6)} = \frac{1}{1{\cdot}6\,(1{\cdot}5)} = 0.$$

This of course implied that the radius of curvature of the anastigmatic image was infinite and the image flat. But the spherical aberration was of course uncorrected so that it was barely feasible to use even an aperture of $F/16$. Then Rudolph and Goerz came forward with their more complex lenses, in which the Petzval condition

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \ldots = \frac{1}{R} = 0$$

was carried out, not so completely as in the case of Schroeder's lens, but in an approximate degree which at the same time enabled them to get the spherical aberrations sufficiently well corrected for a much larger aperture.

Then the Cooke lenses were introduced, in which the positive and negative lenses involved would, if they were all in contact, yield scarcely any focal power at all and the power was obtained chiefly by the axial separation of the constituent lenses. The Petzval condition

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \frac{1}{f_3 n_3} = 0$$

was approximately, but not completely, fulfilled, for the Cooke lens was to a certain extent a compromise. The fact of the lens being composed generally of only three components, two positive and one negative, was of course an advantage on the score of simplicity, but it entailed the presence of certain excentricity corrections of the 3rd order which produced an incurving towards the lens of images of concentric circles as the pencils got beyond a certain degree of obliquity, say 23 to 25 degrees. Such 3rd order excentricity corrections would increase as the fourth power of the powers of the lenses, so that had the Petzval condition been completely carried out the result would have been a more truly anastigmatic flat field in the middle area of the field, but this would be obtained at the expense of a reduced aperture and focal power combined with a much more marked incurving of the images of concentric circles formed by the more oblique pencils. This would have practically meant a curtailment of the useful field of view. The corollary which this fact illustrates is this, that the complete carrying out of the Petzval condition

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \ldots = 0$$

will only pay under conditions which will permit of the excentricity corrections of the 3rd order being practically eliminated, but, as a matter of fact, they can only be eliminated under conditions of greater complication.

And now let us proceed to consider the case of the telescope usually employed for binoculars and here we may most conveniently leave the erecting prisms out of further consideration, after pointing out that they have a slight tendency to make the red image larger than the blue, to produce slight inward coma, slightly to flatten the images in just the same way as do excentricity corrections, and lastly to produce slight barrel-shaped or negative distortion of images of straight lines projected by the objective. But from the point of view of attaining the Petzval condition the erecting prisms have no influence whatever.

Suppose we take the case of an ordinary type binocular telescope with an objective of about 6″ focal length and a Kellner eyepiece magnifying about eight times and fix it up so as to point squarely at a large diagram of radial lines and circles like Fig. 1 placed at 25 feet from the telescope, and then unscrew the focussing eyepiece by 4 diopters. The eyepiece will then project a real image of the diagram subtending 40 to 50 degrees to a distance of about 10 inches behind it. Fig. 2 gives a rough analysis of this image. The field correction usually followed in the case of an apparent field of 48 or 50 degrees is to secure that an image of a concentric circle at 22 degrees or so from the axis shall be in focus at the same time as the centre point of the diagram. That is, if *AF* is the focal plane we shall

have sharp focus for a tangent line at C, 22° from the axis, simultaneously with sharp focus for the centre of the diagram at A. Nevertheless the image as a whole for the concentric circles or tangent lines is not a truly flat one, because of the excentricity corrections of the 3rd order which exist in the Kellner eyepiece. Under more exact observation it is found that the curve on which the images of

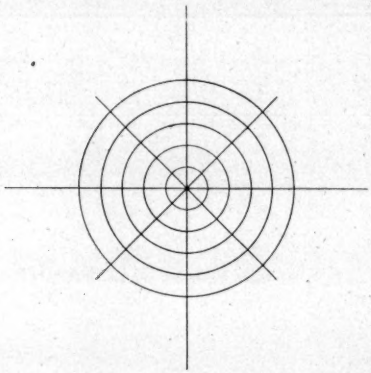


Fig. 1

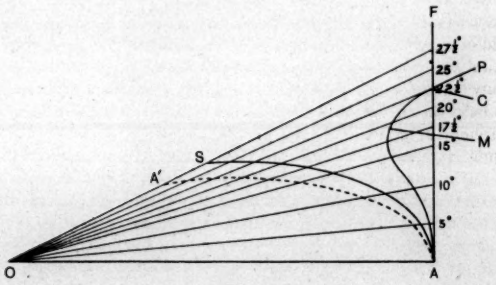


Fig. 2

the concentric circles is formed is the curve $AMCP$, which bulges a little inwards to the maximum point M, about 15 degrees from the axis, then curves back and crosses the focal plane at C and rapidly recedes behind the focal plane towards P. This reversing curve is due to negative excentricity corrections of the 3rd order being counteracted by positive excentricity corrections of the 2nd order. If we now turn our attention to the image of the radial straight lines we find that it is

located along the violent curve *AS* at an ever increasing distance within the focal plane as the angle of obliquity increases, and obviously the reciprocals of the horizontal distances between the secondary curve *AS* and the primary curve *AMCP*, for the same ray, are a measure of the astigmatism existing in the oblique pencils. If the excentricity corrections were only carried far enough to give an anastigmatic image it would then be formed on the still more violent dotted curve *AA'* (whose radius of curvature near the vertex *A* is only ·78 inches), but in order to see such an image clearly the eyepiece would have to be moved further and further in as the edge of the field was approached. Thus, if either a diagram like Fig. 1 or a natural landscape or view containing radial and tangent lines is viewed through any existing binocular, it is found impossible to see both lines in clear focus at the same time. While the image of tangent lines may be approximately flat yet that for radial lines is violently curved, while any markings of the nature of spots or dots are necessarily blurred and elongated tangentially by the astigmatism which accompanies the defect.

I have examined some binoculars made by Zeiss in which the curve *ACP* is curved still further back away from the focal plane, presumably with the intention of simultaneously flattening the secondary curve *AA'* a little more, but personally I do not think that any flattening of the field further than that shown in Fig. 2 is desirable, since it also increases the separation between the secondary and primary curved fields and therefore increases the astigmatism.

I had long ago been impressed by the obviously imperfect field corrections of all existing low power telescopes and about two years ago thought I would enter into an investigation with a view, if possible, of applying the principle involved in the Cooke lens for eliminating these defects and securing a really flat and anastigmatic field of view. I think that you will all agree that no designers who entertain a high ideal of optical science and its applications should neglect any possible opportunity that occurs to them of improving the performances of optical systems, even if it be at the cost of greater complexity in construction.

The arguments in favour of an anastigmatic and flat field of view scarcely need emphasising. It is highly desirable from an aesthetic point of view alone, and this becomes an ever stronger factor under the educative influence of improved standards of optical performance. The binocular is largely used for finding objects, sometimes minute and in unknown localities, in the landscape and to that end it is most important that the eye should be able to pick them up anywhere within the limits of the field just as readily as at the centre. A particular case of this is when they are used by officers of the Navy or Army for observation of fire, and by surveyors and naturalists when exploring new country and by sportsmen whether in looking out for game or in watching races or looking out for friends on the race course.

My enquiries and experiments, carried out with all the facilities afforded to me by the Company with which I have the honour to be associated, at last materialised in the model, first of a power 10 and then a power 7 telescope, in which I am glad to say the perfection of the optical corrections throughout an apparent field

of 52 to 56 degrees came out far higher than I was prepared to anticipate. For I expected to be up against very serious residual aberrations of the 3rd order which could not be got rid of, but eventually the power 10 model, and still more the power 7 model, only showed traces of aberrations of the 3rd order which are so small as to be practically imperceptible. Fig. 3 is a longitudinal section through the optical parts of the power 10 telescope.

I will deal first with the telescope itself and then the erecting prism *P*. *O* is the objective, which is of a type giving a little inward coma to neutralise the outward coma characteristic of the eyepiece system. *N* is a quadruple negative lens consisting of two negative lenses of fluor crown cemented to and enclosing a positive of extra dense flint and a detached negative lens also of fluor crown. As this negative system has to have a very large aperture compared with its focal length, it is necessary to use crown and flint glasses of as widely different dispersive powers as possible in order to keep the curves moderate. I tried at first to make this negative corrector lens a cemented triplet, but had to give it up for the curvatures were so violent that very serious 3rd order aberrations were introduced which could

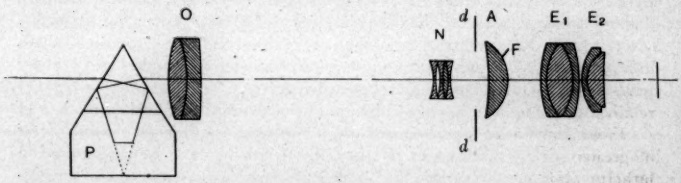


Fig. 3

not be counteracted. This negative system is placed a little within the principal focal plane of the objective and it functions as an enlarging lens, enlarging the primary image and throwing it back on to the plane *dd* where a field stop is placed to outline the field. *F* is a meniscus shaped field lens of dense barium crown whose chief function is to collect the principal rays diverging from the negative lens and render them approximately parallel before entering the eyepiece lenses E_1 and E_2. The first eyepiece lens E_1 is a light baryta flint positive lens cemented between two meniscus negatives of extra dense flint glass. The eye lens E_2 is made of a meniscus extra dense flint lens cemented to a meniscus positive lens of the same glass as that used for the positive of E_1. These two compound lenses are held together almost touching and are together moved in and out by screw action, according to a diopter scale engraved on the eyecap.

The image is supposed to be formed always in the constant position *dd*, while focussing for short distances is done by moving the objective outwards, and for varying eyesight it is done by screwing the eye lenses in or out. The forms taken by these various lenses have been with a view to eliminating aberrations of the 3rd order as well as those of the 2nd order. Here then is shown the application to the telescope of the same principle of construction as was first embodied in the

Cooke photographic lenses, only in this case the principle is carried out still more thoroughly and with still more perfect results.

As I have pointed out before, one can only carry out the Petzval condition completely, provided that aberrations of the 3rd order can be eliminated completely. In the case before you the whole Petzval sum

$$\frac{1}{f_1 n_1} + \frac{1}{f_2 n_2} + \dots$$

comes out not exactly zero, but with a very slight minus residue of 1·6 per cent., which enables it to present to the eye an image that is perhaps a little better than being anastigmatically flat, inasmuch as it is really not only anastigmatic but slightly curved concave to the eye, to about 19 inches radius. I would lay a little stress on this point, as I think it will be conceded that the average user of a binocular so focusses that the axial distance from his eye of the virtual image presented to his view is not infinity but generally about 20 inches and it therefore becomes desirable that when turning his eye to see an object at the edge of the field he should not have to vary the focus of his eye, and for that reason I aimed at getting the radius of curvature of the anastigmatic image about 20 inches, and concave towards the eye.

The longitudinal section of the power 7 system would not look essentially different from that of Fig. 3, the main variation being that the objective is of shorter focus and the negative lens enlarges the image in lesser degree and has a larger relative aperture, while the whole telescope is a little shorter.

From what I have already said it will be inferred that these two telescopes are of greater perfection, from an optical point of view, than was any Cooke lens hitherto worked out and this is due to the greater complication or the greater number of elements which can be intermodified in order to suit all the exigencies of the case. I remember visiting Zeiss's factory in 1894, together with Mr Wigglesworth, and having a very interesting talk with Prof. Abbe on the subject of attaining greater perfection in the performance of optical instruments, and his emphatic declaration was that, as a general rule, one should never be afraid of adopting greater complexity in construction, provided that any substantial gain in optical performance were thereby secured.

And now we have got an anastigmatic flat field telescope, but it is an inverting telescope, and means of erecting the image must be found. The ordinary pair of crossed doubly reflecting right-angled prisms placed between the objective and the negative lens might be employed, but there are very grave objections to their use in this case.

I think most of you here will agree that one seldom comes across a pair of prismatic binoculars in which a critical examination will not reveal a lob-sidedness of the field corrections, I mean a greater amount of astigmatism or flatness showing on one side of the field than on the other or more coma on one side than the other. Nor need one be surprised, when it is considered how essentially intricate and difficult the adjustments of such prisms really are. First of all, we have lateral movements of the prisms along their lengths and parallel to themselves, which

separately or jointly cause the objective and its optical axis to shift about laterally with respect to the eyepiece, and then the angular tilting of the prisms about their long axes due to imperfect bedding, which separately or jointly cause the objective apparently to shift laterally and the optical axis of the objective to tilt at various angles to the eyepiece. Let us remember that while a certain degree of maladjustment may pass unnoticed in the case of a telescope whose field corrections are in the first place very imperfect, yet the same degree of maladjustment would be noticed at once in the case of a telescope with much more perfect field corrections.

It therefore seemed to me highly desirable to devise an erecting prism that would in the first place be all of one piece of glass and in the second place be fixed just in front of the objective, in which case its adjustments would be comparatively much more simple and straightforward than in the case of the present erecting prisms. An end view of this erecting prism is illustrated in Fig. 4*A* and a side view

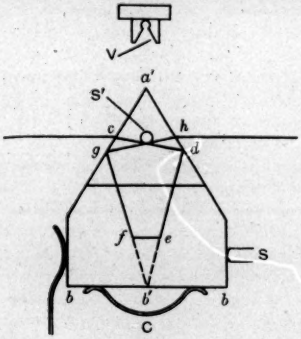


Fig. 4*A*

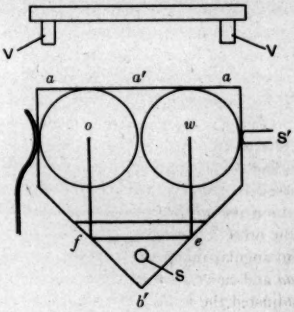


Fig. 4*B*

in Fig. 4*B*, which is the view of the prism from the telescope side, the right-hand objective being outlined on the left and the corresponding opening or window on the right where the light enters the prism. The angle of the prism at *a* is generally 62 degrees and forms the top ridge *aa* in view *B*, which is at right angles to the lower ridge *bb* formed by the two plane totally reflecting surfaces containing the right angle. It will easily be seen that the two plane surfaces containing the upper angle of 62 degrees act both as transmitting surfaces and as totally reflecting surfaces as can be seen better in the end view *A* of the prism, where the axial ray is shown entering the outer surface at *c* and being refracted down to *d* on the opposite surface where it is totally reflected down to *e* on the median line of the near roof surface. It is next totally reflected diagonally across to *f* on the median line of the far roof surface and then totally reflected up to *g* on the first transmitting surface, whence it is totally reflected up to *h* on the second transmitting surface where it is refracted through and passes out in a direction parallel to the entering ray but laterally dis-

placed by about half the length of the prism. The field of total reflection depends upon the refractive index. For a power 7 telescope which requires 8 degrees of actual field the refractive index should not be less than 1·58 and a light flint, which is one of the most transparent of all glasses, should be employed. For an objective of 1 inch aperture it is well known that the inside glass path involved in the usual double crossed prism is about 4 inches and the same applies to this new prism, although there is slightly more bulk of glass involved.

Now it will be seen that there are only two movements of this prism that can move the image in the field at all. One is an angular movement about any axis parallel to the vertical axis *a'b'*, and the other is an angular movement about any horizontal axis parallel to the top ridge *aa*. The first movement moves the image left or right by twice the angular movement of the prism and the second moves the image upwards or downwards by twice the angular movement of the prism. The top ridge rests in two V-cut claws *V* and *V*, one near either end, and is pressed home into the same by a counterspring *C* pressing on ridge *bb*. These two V claws are part of a flat bar resting upon a flat surface at the bottom of the prism box and this flat bar can be moved laterally parallel to itself, thus giving an angular movement of the prism about an axis parallel to the ridge *aa*, there being a fixed bearing point *S* (Fig. 4*A*) against which the prism is kept pushed by spring pressure opposite. That is, the lateral movement of the V bar gives an angular movement of the prism about a horizontal axis and vertical movement of the images, the prism adapting itself by rocking slightly in the V claws. The V bar is also capable of a rotation about its centre, that is, one V can be made to recede from the telescope while the other V approaches by an equal amount, and this movement of course imparts an angular movement of the prism about a vertical axis perpendicular to the ridge *aa* and causes horizontal movement of the images. After the prism has thus been adjusted the V bar is securely fixed. Of course none of these adjustments of the prism have any effect whatever upon the optical performance of the telescope; it is only the orientation of the images that is affected.

It will be seen that this prism and the methods of its mounting imply a great simplification in the adjustments, moreover these adjustments are so arranged that they can be operated from outside by concealed screws while the binocular is all assembled and directed on a test mark. After the adjustments are carried out the operating screws, which lie concealed in their recesses, are sealed up and fixed.

I would here point out that the form of eyepiece which has been shown in section in Fig. 3 is, with a slight modification, also applicable to the microscope. But as microscope objectives, on the dry system at any rate, may also be constructed to give anastigmatically flat images, it becomes desirable to make the eyepiece anastigmatic and with a flat field in itself. In the case of the telescope it has to be over-corrected in order to neutralise the field curvature and astigmatism of the objective and the more so in inverse proportion to the magnifying power. In the case of the microscope each different power of eyepiece should be equally usable with any power of anastigmatic and flat field objective and thus be interchangeable. I hope to bring before you more detailed accounts of such schemes of microscope

construction on some future occasion. It will be seen that these more complex constructions for telescopes imply six cemented pairs of surfaces and it becomes important that the films of Canada balsam shall be as colourless as possible as well as permanent, and here we are up against the ever recurrent balsam problem, the well-known difficulties of which I think I have succeeded in solving in a very simple and practical way, which, if confirmed by further experience, would in itself furnish material for a short paper.

Lastly, as regards complexity in construction, I would point out that there is nothing of special difficulty in it, although, of course, it must be expected that the cost of production of the optical parts will appreciably exceed the cost involved in the ordinary construction. But I have never heard yet that in the case of bicycles, motor cars, gramophone records, orchids, or potatoes a more thorough realisation of the ideals aimed at in each particular instance has been attained, without calling forth more ready and appreciative offerings from the purses of those who really want such things.

DISCUSSION

Mr L. C. Martin drew attention to a paper by Prof. Conrady in the Monthly Notices of the *R.A.S.* (April, 1918) in which the employment of an achromatic negative lens before the positive lens system of the eyepiece is suggested in order to produce an anastigmatic flattening of the field by satisfying the Petzval condition.

He would like to enquire whether, in the author's opinion, the gain in definition at the margin of the field would be sufficient to compensate for the effects of multiple reflections in diminishing the light and weakening the contrasts in the image.

Mr H. S. Ryland said that of about 4000 binoculars which he had examined 92 per cent. possessed unequal astigmatism.

He would also like to draw attention to the question of the loss of light. He thought it was better to have good definition at the centre of the field of view accompanied by good illumination than to have good definition over the whole of the field with inferior illumination, provided that the definition does not fall off too badly. In practice the periphery of the field was largely used for detecting movements of objects.

He suggested that manufacturers should publish light transmission values in their advertisements.

Instructor-Commander T. Y. Baker thought that the author was to be congratulated on introducing a new method of erecting the field of view by means of prisms.

He asked if the author could give the percentage light transmission of his telescope, as this was an important factor in service instruments used for night work. Recently attempts had been made to reduce the loss of light in prismatic binoculars by cementing the reflecting prisms together and to the flat face of the field lens, thus giving six glass-air surfaces as compared with four in the Galilean binocular. He enquired if it would be possible to simplify the eyepiece in the author's telescope so as to reduce the number of glass-air surfaces.

Mr P. F. Everitt agreed with the author that any complications in optical design were justified if they led to improvement in performance.

He thought that the question of astigmatism in binoculars was one of long standing.

Mr T. Smith said that the little prism in front of the system was very compact and could easily be seen to be achromatic. The condition for this was that the bisector of the angle between the two refracting faces should be perpendicular to the roof edge. It would be interesting to know how this was secured in manufacture.

It had been stated that the Cooke lens had been so designed that when all the lenses were placed together the combination was of zero power. In any system of separated lenses the sum of the powers of all the components enters into the aberration expressions and particularly affects the astigmatism as distinct from the curvature which depends on the Petzval sum. The sum of the powers need not be zero, but its value will affect the design considerably. He cited by way of example any system in which each successive image formed by the various lenses was free from spherical aberration and coma; the vanishing of the sum of the powers was then the condition for freedom from astigmatism. This in conjunction with the Petzval condition suggested that by the introduction of a negative field lens existing telescopes could be given a flat field free from astigmatism.

Mr J. Guild said that he would like to oppose the view that the only thing which matters is the brilliancy of the image, as he considered that the visibility in faint lights must depend largely on the accuracy of the definition.

The author, in reply, said that he did not think that the telescope could be simplified.

With regard to the loss of light he wished to draw attention to the enormous adapting power of the eye to variations in brightness. The illumination of a landscape under a full moon is well known to be at least 300,000 times weaker than in broad sunlight. In a particular submarine periscope system the light transmitted was only about 20 per cent. yet a friend had declared that objects seen through it appeared to be as bright as under ordinary circumstances. In the telescope described in the present paper about 40 per cent. of the light is transmitted when the surfaces are freshly polished. About five of the surfaces retain their polish, while the others tarnish and then transmit more light. After the instrument has been in use for some time it transmits about the same percentage of light as an ordinary prismatic binocular.

The most important question to be considered is that of the balsam, which in tropical climates dries and cracks, a certain amount of volatile constituents evaporating out and giving rise to vacuities and further trouble. He thought that he had found a way of getting rid of the brittleness of the balsam, and he hoped shortly to give a paper dealing with the balsam problem.

He estimated that the cost of the binocular would not exceed that of an ordinary prismatic binocular by more than 50 per cent.

Note added later. I was not aware of Prof. Conrady's paper in the Monthly Notices of the *R.A.S.* until after Mr Martin drew my attention to it. I then procured a copy, from which I find that Prof. Conrady was, as should be expected, fully aware of the importance of carrying out the Petzval condition in eyepieces for telescopes, but should he have proceeded to work out practically such an eyepiece, I feel sure he would have found that it cannot be efficiently carried out by the employment of only one cemented compound negative lens and one cemented compound eye lens, as suggested in his paper.

A SHUTTERLESS, CONTINUOUS-FEED KINEMATOGRAPH

By R. J. TRUMP, B.A., B.Sc., A.Inst.P.

Read and discussed, 10th February, 1921

The purpose of this paper is to give an account of the optical details of the projector, the invention of Mr Kingsley Higginson, which was demonstrated before Fellows and Members of this Society earlier in the evening. The general principle involved is that a record film, taken in the ordinary manner, is run continuously through the machine, the image being kept steady, and the change of one picture for another being effected by a ring of mirrors, which is continuously rotated. The shutter and intermittently acting film-feeding gear of the ordinary machine are thereby eliminated. There is no periodic shutting off of the light, as takes place in the shutter machine. The screen is always fully illuminated, and the image completely fills it. The only optical elements employed, in addition to the usual projector lens, are plane reflecting surfaces, so that there is no disturbance of focus, and no refractive aberrations have to be taken into account.

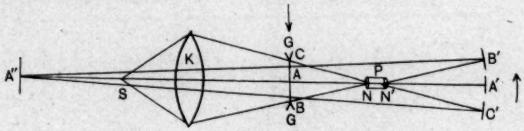


Fig. 1

Let it be assumed that the light from a source S is focussed by the condenser K upon the back nodal point N of the projector lens P (Fig. 1). Then if all the light which emanates from any given point on the film be regarded as constituting a narrow pencil around the line joining that point to the point N, the corresponding emergent pencil will proceed as from the emergent nodal point N', in a direction parallel to its original course. The point N' may then be regarded as constituting the centre of projection, or "radiant point," of the emergent beam.

In Fig. 1 let A be the central point of a film-picture standing squarely in the gate G. A mirror placed at A' will reflect the ray AN, which emerges as $N'A'$, back to A'' if the light be assumed not to be impeded by other parts of the apparatus. If now A moves to B, the ray AN becomes BN, and $N'A'$ becomes $N'B'$. The mirror must now be moved round to follow the ray, and at the same time it must be inclined to bring the reflected ray back to its proper point of incidence A'' on the screen. The angle of inclination necessary to obtain this result is clearly equal to one-half the angle ANB *plus* one-half the angle $A'A''B'$. If now C be the position

of the point A at an instant half a period earlier than that shown, C and C' will be symmetrical to B and B' on the other side of the axis. The angle through which the mirror must be inclined to maintain the image of the mid-point of one film-picture at the point A'' during a whole phase of the movement of the film is therefore equal to one-half of the angle subtended by a picture at the nodal point of the lens when in focus, *plus* half the angle subtended at the screen by the distance through which the point of incidence of the emergent ray upon the mirror moves in space.

Consider now a complete object-picture BC, Fig. 2. This subtends a certain angle at the nodal point N, and the emergent principal rays include the same angle. When the picture is in its central position, the mirror must also be centrally placed, so as to reflect the image squarely upon the screen $B''C''$. Any movement of the

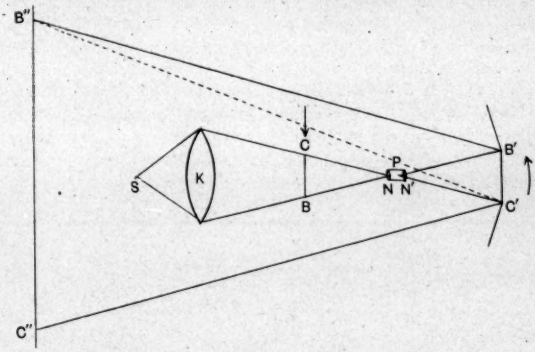


Fig. 2

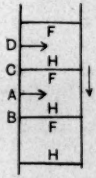


Fig. 3

film, by presenting a portion of the next picture, must immediately bring the next mirror into play; or in other words, the limiting ray CN of a picture must impinge upon the intersection of two successive mirror facets. Moreover, it will be seen that it must continue to do so throughout, for at the point C there is a discontinuity of image upon the film. Referring now to Fig. 3, suppose that each film-picture carries a photograph of a standing subject. This is run through in the inverted position, and erected by the projector lens as usual. The point C therefore corresponds to the feet, F, of the subject, and the point immediately above it to the head, H, forming part of the next film-picture. For correct rendering, therefore, the rays from the entering picture must be reflected to the top of the screen, whereas the mirror $B'C'$ would direct them to the bottom. A second mirror facet must therefore come into position, and it must be set at such an angle to the first as to transpose the two partial pictures which are then in the gate into their proper positions, and join them up to form a complete image on the screen.

This transposition will be perhaps more obvious from Fig. 4, which shows a mid-way position, where half of one picture has left the gate, and half of the next has entered it. *A* represents the central point of one picture, standing now at the edge of the gate; *C* is the point of discontinuity, and *D* is the central point of the second picture. Parts of two mirrors are in action, and they now stand symmetrically at an equal inclination to the axis of the system. The ray *AN*, emerging as *N'A'*, falls upon one reflector *C'A'*, and is directed to the centre of the screen. The ray *DN*, emerging as *N'D'*, is received by the facet *C'D'*, and also directed to the centre of the screen. The light from the point immediately above *C*, the head portion of the supposed subject, falls just below *C'*, on the lower mirror, and is directed to the top *C'''* of the screen, while that from a point below *C*, the feet of the subject, is directed by the facet *C'A'* to the bottom *C''* of the screen. The

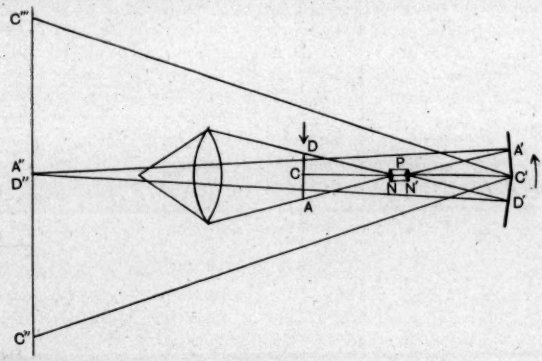


Fig. 4

effect of the mirrors, therefore, is, as it were, to divide the picture as it stands in the gate along the line of discontinuity at *C*, and transpose the two parts into a complete image by joining up the corresponding parts *A*, *D* of the two successive pictures.

By comparing Fig. 4 with Fig. 1, it will be seen that the angle between successive facets which is required to effect this transposition is precisely the same as that which marks the extreme positions of the same facet in order to maintain the stability of the centre point of the image on the screen. That is to say, the image of the point *D* is thrown upon the centre of the screen the moment that point makes its appearance in the gate, and its image will remain there as the film moves, until the moment it reaches the bottom of the gate. The facet *D'C'* will then have reached the position corresponding to *C'A'* in Fig. 4. By this time a third film-picture will be in the mid-way position, and another facet in place to transpose it.

A complete ring of mirrors, making with each other an angle equal to the angle $D'C'A'$ will suffice to give continuous operation. At other intermediate positions the transposition is effected in a similar way; and as the two partial pictures in the gate always add up to one complete picture, however much of each one be present, so also do the two transposed partial images add up to form a complete image on the screen.

In this idealised system it will be seen that the mirror has to receive a movement of translation equal to that of the movement of the point of incidence of the ray upon it, and also at the same time its direction must be varied at rather more than half the rate at which the inclination of the ray changes. To a first approximation at least, these conditions are satisfied by rotating the mirrors about a centre which

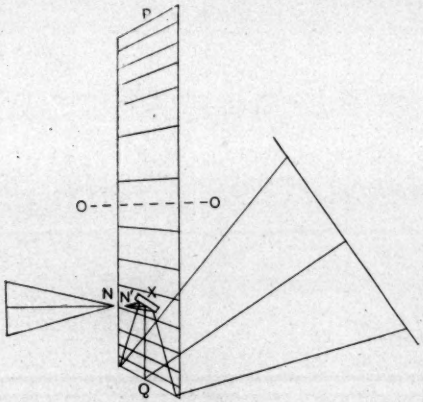


Fig. 5

is nearly twice as far from the face of each mirror as is the nodal point of the projecting lens at the time when that mirror becomes operative. It would not be profitable to proceed further at the moment, because the system as actually required will introduce substantial modifications. The reflected rays must by some means be turned aside, so that they can pass to the screen unobstructed by any part of the apparatus.

The arrangement actually employed is shown in plan in Fig. 5. The axis of rotation OO of the mirror-ring is parallel to the optical axis of the projecting lens, and a small fixed mirror X is adjusted to throw the light sideways upon the facets of the revolving mirror-system PQ, the angle of incidence being such that the reflected beam is thrown clear of the mirror X. The various facets of the rotating system are somewhat tapering in outline, and are arranged to form the frustum

of a pyramid. At this point the main lines of the optical system have been fixed, and there remains only the computing problem. It has to be ascertained whether such a system is practicable, and if so, what are the necessary data for it.

At the very outset, there is one fortunate circumstance that will be noted. A complete ring of flat mirrors, forming in section a regular polygon, can only be varied by increasing or decreasing the number of its faces one at a time, and the angle between adjacent faces changes step by step. If, therefore, they were arranged in prismatic form, and the light were incident in a principal plane, the change in direction of a ray produced while one face proceeded to take up the position of its predecessor would be fixed at twice the angle between successive faces of the prism, and would not be continuously variable. The most suitable number of facets would have to be selected, and the lens then adjusted in power to suit this value. The pyramidal arrangement, however, introduces another variable, since the rays are no longer incident in a principal plane, and the cosine of the angle of obliquity comes in as a factor to determine the deviation of an incident ray for a given inclination of the reflecting surface. The variation of the obliquity enables the mirror to be suited to a given lens. As the obliquity actually employed is small, the cosine is insensitive, and quite a fair margin of error is admissible, a point which makes for convenience of construction.

It was at first assumed that a considerable angle of obliquity would be employed, and that the mirror facets would require to be formed so as to constitute the necessary oblique sections of the pyramid of light defined by the principal rays starting from the outline of the film-gate; and that at the same time, they would have to be shaped so that an integral number of them would fit round in a complete circle.

The correction for the central ray gives no serious trouble, and this ray can be almost perfectly stabilised upon the screen. The various approximations involved, and there are several of them, have but a slight effect, for only small angles come into the question. The vertical edges, however, are not readily amenable to treatment. The kind of effect that comes in may be roughly indicated as follows. A rectangular pyramid of light, cut by a plane mirror inclined to its base, gives a section $WXYZ$, Fig. 6, which is tapering in shape, and the reflected light, caught upon a plane parallel to the mirror, will show a patch of light $W'X'Y'Z'$ of similar shape. Suppose that one film-picture is represented by a thin transparent line along one horizontal edge; this will appear upon the screen marking out one edge of the patch of light, as $W'X'$ and will be at an angle to the centre line, supposed horizontal. If the mirror be kept stationary, while the film is fed forwards, the bright line will travel across the screen until it reaches the other extreme edge $Z'Y'$ of the light-patch, but its direction will steadily alter, as it becomes horizontal at the mid position, and then takes an inclination in the opposite direction. Upon then tilting the mirror about its centre-line RT to bring the bright line back to its original position at the bottom of the screen, it will be seen that, at the best, it can only be made to take up the position KL, parallel to $Z'Y'$, and inclined to $W'X'$. Hence when the vertical centre line is corrected, there is over-correction

at the edge $Z'W'$, and under-correction at the edge $Y'X'$. Upon a screen perpendicular to the central ray the resultant unsteadiness of the image is slightly more than upon a screen parallel to the mirror.

As we are here dealing with an effect that arises simply from the obliquity of incidence of the light upon the revolving mirror, the first step to improve matters is to reduce this angle as much as possible. The taper of the facets then becomes very small, and can practically be ignored. The full size of each film-picture is $\frac{3}{4}'' \times 1''$, but it is masked down in projecting to $\frac{1}{16}'' \times \frac{1}{16}''$. The gate can be reduced in width to $\frac{1}{18}''$, but its height must be made equal to the full height of a picture. The remaining $\frac{1}{32}''$ at the top and bottom edges is therefore left available. Thus in Fig. 7, if *ABCD* be the projection of the film-gate superposed upon a facet having the shape *WXYZ*, the fact that these two outlines are not exactly alike can be ignored if the parts shown by the shaded strips can be masked off. This possibility also obviates the necessity of butting the mirror facets hard up to each other, thus considerably facilitating manufacture.

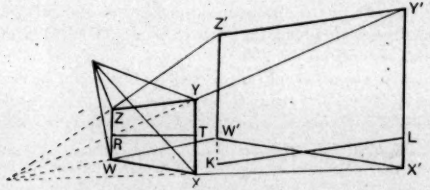


Fig. 6

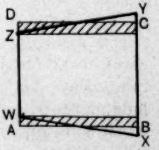


Fig. 7

A full description of the computing methods employed would scarcely be of sufficient general interest to warrant its being given *in extenso*; it is essentially three dimensional, in that it is required to trace the paths of rays moving in a vertical plane, and incident obliquely upon a mirror rotating about an axis inclined to its own plane. Quite a number of errors are to be expected, but it was found that only those affecting the direction of the final ray needed to be taken into account. The bodily displacements arising from the wandering of the point of incidence upon the mirror were in all cases small—of the order of a few hundredths of an inch—and could be ignored, a great simplification in working resulting. The vertical movement of the ray was taken to a first approximation only. The most suitable number of facets for the mirror-ring was found, and the final adjustment of the central rays obtained by varying the obliquity, as above described.

In addition to keeping the angle of incidence upon the rotating mirror as near the normal as possible, there is another resource available. The shape of the projection of the gate upon the mirrors can be brought nearer to the rectangular shape by slightly inclining the film to the axis of the system. The pyramid defined by the emergent principal rays is no longer a right pyramid, and a rectangular section can be obtained by a plane which is not at right angles to the central ray. It is

not desirable to employ an angle sufficient to obtain this result fully, but a distinct advantage is secured by an inclination of a few degrees. The loss of focus at the edges, when using a hard source of light such as the arc, is inappreciable, while a distinct gain in steadiness of the picture is obtained. A small lateral deviation of the reflected rays also takes place, owing to the fact that whereas each principal ray traces out a fan of light, lying always in one plane, the normal to the mirror follows the surface of a cone, and these two movements cannot exactly compensate each other.

The question of definition is one that required a considerable amount of thought. There was no information available as to what would be the amount of tolerance of the eye when translated into permissible movement of the image upon the screen. The conditions of observation are obviously not exacting. A somewhat dazzling, moving image is projected upon a distant screen under conditions that are not calculated to render the recognition of the finest detail at all possible. Moreover, the distribution of the residuals in this system is the best that could occur to avoid any serious effect upon the image. The centre of the field is corrected to a high degree of accuracy, so that the clearness of the important parts of the picture is assured. The maximum disturbance is found towards the corners, but the only result there, even with errors of considerably greater magnitude than it has been found necessary to admit here, would be merely to soften away the finer detail of the background, which the eye would probably not appreciate in any case, even if clearly presented. The effect is, in fact, comparable with that of a little roundness of field in the projector lens. Judged by the eye during running, which is the only test having any real meaning, the definition of this machine is fully up to all requirements. Indeed, it has to be deliberately put considerably out of adjustment before the eye can detect any visible deterioration in the image. The actual setting-up of the apparatus showed that one's original ideas as to the accuracy demanded must be greatly modified. The tolerance of the eye appears to be much greater than was anticipated.

Although originally designed for a particular projection distance, a further examination of the calculations upon which the mirror was constructed showed it to be adaptable over a wide range. Upon reference to Fig. 1 it will be seen that the angle between the extreme paths of a principal ray, after reflection at the mirror, is the subtense of the width of one facet at the screen. If the screen be removed to a greater distance, these two paths will have crossed, and begun to separate, before the screen is reached; that is, they will be converging more rapidly than is required to secure proper correction. It will now, however, be necessary to refocus, bringing the lens a little nearer to the film, and thereby increasing the initial angle between the extreme paths of the principal rays. The increased divergence of the emergent rays compensates in a very large measure for the increased screen distance. The residual error is very small, but can if necessary be altogether removed by a slight adjustment of the cell of the projector lens.

Upon the mechanical side of the machine it is perhaps scarcely profitable to enter, as it is quite likely that questions of manufacturing cost may involve certain

modifications. The main shaft occupies an intermediate position in the gearing, so that both the mirror-ring and the film-sprockets lag back upon the drive, thus avoiding back-lash. Direct gearing is employed so as to maintain accurately the synchronism between the mirrors and the film-feed. A differential gear is fitted to ensure correct "framing," should it be thrown out by bad joining-up of the film. The mirror-facets are constituted by separate plates of stainless steel, screwed down solidly upon flats ground upon the inside of a carrier-ring running on ball bearings. Metallic facets of this character have a great advantage in that they can so readily be fixed, but the particular sample of metal employed in this machine does not appear to be very homogeneous, and the polish is not holding up very well. The reflecting efficiency of this material was not known at the time the mirror was under construction, but the figure given by Mr Guild at a recent meeting of this Society shows it to be rather less than was anticipated. With a more suitable choice of the reflecting material, a considerable improvement over the 50 per cent. photo-efficiency of a shutter would be obtainable.

The author desires to express his thanks to Mr T. Smith for the kind interest he has shown throughout in the progress of this investigation; and particularly for the great encouragement received at a time when serious doubts were thrown upon the reasonableness of the primary assumptions upon which the whole of the work was based.

DISCUSSION

Mr T. Smith congratulated the author on the successful conclusion of his work. He asked what was the peripheral speed of the wheel carrying the mirrors in normal working of the projector.

Mr J. W. Hasselkus considered the apparatus a beautiful piece of work regarded as a scientific instrument, but it had not in his opinion yet reached the stage at which it could be regarded as a commercial success. He thought the principle utilised, which caused no individual picture to remain undisturbed for an appreciable interval, rendered the attainment of beautiful definition impossible under any circumstance.

Dr E. H. Rayner said that in taking the photographs about 16 exposures per second were usual, but some 50 per second were usually shown on the screen. For special purposes high speed machines taking up to 100 pictures a second had been made, but it was most important that means should be devised for securing from 300 to 500 pictures per second. He suggested that this design might perhaps enable this to be done by working in the reverse direction. The excellence of the results shown on the screen in any cinematograph was, he thought, due to the general impression from the mass of pictures being better than that shown by any one single film, the local imperfections and grain of any one picture being drowned by similar structure in succeeding ones not coming in the same place.

Mr R. S. Whipple said that about 18 years ago The Cambridge Scientific Instrument Company spent two years in the construction and development of a cinematograph projector, using a continuously moving film. The instrument was invented by Mr A. Hatton, who employed two mirrors, actuated by cams, and two projecting lenses to throw the pictures on to the screen; the pictures were superposed. In practice, one mirror followed the movement of the film, keeping the picture stationary on the screen. When the width of the picture had been traversed that picture was occulted and a picture from the second mirror was shown. Alternate pictures were, therefore, shown by the mirrors. The result was extremely good. The pictures were steadier than any others exhibited at that time, and showed clearly that to obtain perfect results the films must be taken by a camera operating on the same principle. Such a camera was made, but, unfortunately, no picture was taken with it. The inventor and the financier had a serious disagreement, and the experiments were discontinued. To the best of his knowledge no further experiments had been made with the apparatus. He regarded this as the greatest instrument tragedy that he had known.

The author, in reply, said the mirrors moved about 18 inches a second. He was not in agreement with Mr Hasselkus about the definition, for all that is thrown on the screen was well defined, the changing of the picture along successive zones instead of all over at once having no influence in this respect. It must of course be remembered that in this as in all other cinematograph systems they were essentially producing an illusion from beginning to end. The question of the reversal of the system for photographic purposes had not been lost sight of. But it was not yet quite certain that the original assumption would continue to be valid, as they were then concerned with wide pencils filling the lens, while in projection the pencils were narrow and by no means filled the aperture of the projecting system.

NOTE ON THE GALILEAN BINOCULAR

By T. SMITH, F.Inst.P.

MS. received, 13th January, 1921. Read and discussed, 10th February, 1921

Recently two communications have been presented to the Optical Society dealing with the enlargement of the field of view of the Galilean binocular, and the conclusions reached in the two cases disagree. It may be as well to record in the Transactions the quantitative relations which govern the problem, as they have not been included in either of these earlier communications.

The diameter of the objectives is usually made as large as mechanical considerations will permit, and may be taken as a constant. The magnifying power is assigned, and any improvement that may be possible must, so far as it is determined by the quantities considered in these discussions, be reached by reducing the separation between the exit pupil and the eye lens. This separation is reduced in proportion to the overall length of the instrument by shortening the focal length of every lens in the same ratio, and in a well designed instrument where an increased field is the principal aim this reduction will be carried to the extent which is found consistent with good definition as the aperture ratios of the component lenses rise. It may therefore be assumed that at any rate one of the lenses in the ordinary form has reached the limiting power that can be permitted to it. The question for discussion then is, can the field be appreciably increased without violating these conditions for the limiting powers by introducing a third lens, and if so what must the character of the new instrument be?

For the purpose of this discussion a system of three separated lenses is sufficiently specified when the powers of the three lenses and the two separations are known. The lenses need not be thin if measurements are made from the principal points. Two relations must exist between these five quantities, one expressing that the system is telescopic, and the other that its magnifying power has the required value. Thus three of them may be taken as independent variables. It is convenient to take for these one of the separations, since in practice these are necessarily positive, the power of the lens which has reached its limiting value, and the power of the lens which is introduced to render a larger field possible. This may be assumed to be the central lens at the moment, and it will become evident that no further case need be considered. Denote the powers of the three lenses—objective, new lens, eye lens—by k_1, k_2, k_3 respectively and their separations by t_1 and t_2. The magnifying power is m and one of the fundamental Gaussian functions of the system will be called T where

$$T = t_1 + t_2 - t_1 t_2 k_2.$$

The distance between eye lens and exit pupil is T/m. One of the ordinary Gaussian formulae at once gives the relations

$$1 - t_1k_2 = m + Tk_3 \quad \ldots.(1),$$

and

$$1 - t_2k_2 = 1/m + Tk_1 \quad \ldots.(2).$$

Consider first the case when the eye lens has reached a limit but further development is still possible with the objective. Equation (1) gives the value of T for the doublet when k_2 is made zero. T is varied by giving t_1k_2 some value other than zero, and if T is to be reduced t_1k_2 must have the same sign as k_3. Thus since t_1 must be positive k_2 must be negative. In just the same way if the objective alone has reached a limit (2) shows that k_2 must be positive to allow the field to be increased. In either case the improvement of the field is greatest when t_1k_2 or t_2k_2 as the case may be is numerically greatest. These results might be expected. The rationale of the whole subject would appear to be that when a limit to the reduction in length of the instrument has been reached by reason of the increased relative aperture of one lens, further progress can be attained by employing in its place two lenses of the same sign. This suggests that the limiting case for the employment of a triple system will be found when the limit has been reached for the lens where the conditions are normally less severe, unless indeed the doubled lens breaks down earlier.

The greatest gain is secured by placing the new lens as far as possible from the lens which needs no aid. In other words, like lenses should be close together. Where a lens corrected for colour breaks down, it may be possible to cement the new lens to the old; by thus using a multiple cemented lens in place of a simpler one the special advantage of the Galilean telescope, its low absorption of light, may be retained to the fullest extent possible.

It is easy to verify that with the ordinary binocular the objective works under much worse conditions than the eyepiece. A relative aperture for the former of about $f/3{\cdot}5$ is usual. An increase in the field will be brought about by duplicating the objective, and thus enabling an eye lens of shorter focal length to be used. To say that in this case the increased field is due to the more powerful eye lens is analogous to the suggestion that the cart pushes the horse along. On the other hand it is a mistake to separate the two portions of the objective.

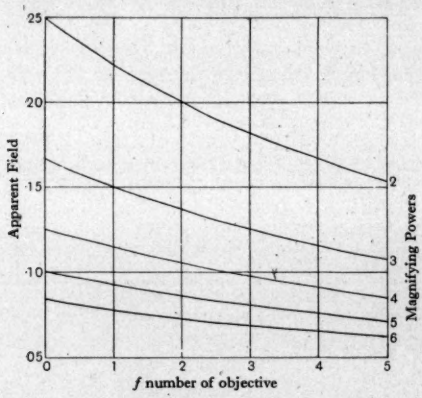
Note added later. Although quite distinct from the question dealt with in the foregoing note, it is natural to ask what extension of the apparent field of view of the Galilean binocular is possible, and the answer is readily expressed in terms of aperture ratios. Let a be the greatest diameter the objective may have, which will be slightly less than the normal separation between an observer's eyes, and suppose that Ω is the irreducible distance between the centre of rotation of the eye and the second principal plane of the eye lens. The diameter of the exit pupil is a/m, and its distance from the centre of rotation of the eye is $\Omega + T/m$. The ratio of these two lengths may be accepted as a conventional measure of the apparent field of view, thus

$$\text{Apparent field} = \frac{a}{m\Omega + T}.$$

Assume that both objective and eye lens consist of tightly packed lenses, so that no separated central lens exists; (2) then gives

$$\text{Apparent field} = \frac{1}{m\frac{\Omega}{a} + \left(1 - \frac{1}{m}\right)\frac{1}{ak_1}}.$$

The ratio Ω/a is about 2 for all observers, and the apparent field thus depends upon the magnifying power and upon the relative aperture attainable in the objective. The striking feature about this result is that the magnifying power should exercise the influence there indicated, for the apparent field in actual



instruments tends to have roughly the same value for different powers. In most Galilean binoculars $\frac{1}{ak_1}$ (the f number of the objective) lies between 3 and 3·5, but values as low as 2 have been employed. However elaborate the construction the value 0 is unattainable, so that the apparent field can never be as large as $\frac{1}{2m}$.

From the accompanying diagram in which the apparent field is plotted against the f numbers of the objective the extent to which improvement is theoretical y possible can be seen. Separate curves are drawn for different magnifying powers covering the range usual in these instruments.

DISCUSSION

Mr H. A. Hughes said that in the paper by Mr Everitt and himself the basis of their improved design was the short radius surface of the eye lens, and this probably explained the point of view from which they had criticised another design. He inferred that the author considered improvement in the field was still possible.

Mr T. F. Conolly said that the thanks of the Society were due to the author for clearly and definitely setting out the limits as to improvement in the field of view of a Galilean binocular. Mr Smith's conclusions as to the effect of an additional (field) lens amounted, in fact, to an increase in the power of the object glass without change of effective diameter. It appeared to the speaker that the design of a Galilean binocular, as regards field of view, had practically reached finality.

Mr P. F. Everitt wrote: The theory of the Galilean binocular is perfectly clear and the matter under discussion really is what is the most convenient method of presenting the same. Mr Smith prefers to use the aperture ratio of the objective to which he has assigned a fixed diameter; this is equivalent to using the focal length of the objective as the controlling factor. Mr Hughes and myself prefer to use the focal length of the ocular, which bears a constant ratio to the focal length of the objective, as the power is always specified before proceeding to the work of designing. Mr Smith's reference to the celebrated suggestion of the cart pushing the horse is a little wide of the mark; the difference between our respective points of view is more akin to one man specifying an ellipse of given eccentricity by the length of its major axis and another man using the minor axis. It is not a matter of any importance.

There is the important fact concerning the use of a third lens or system in a Galilean, and it is very gratifying to have Mr Smith's valuable support to my conclusion that such a lens to give maximum gain in field must be amalgamated with either the objective or ocular according to the sign of its focal length.

The author, in reply to Mr Hughes, agreed that theoretically some little improvement was possible, but it was doubtful, except perhaps in the case of very low powers, whether the advance justified the additional complication. Mr Conolly's statement summed up the situation shortly. It might be noted that the theoretical limits to the apparent field increased considerably as the power fell, if the relative aperture of the objective were the ruling factor.

TRANSMISSION OF LIGHT THROUGH A PILE OF PARALLEL PLATES

By Instructor-Commander T. Y. BAKER, R.N., B.A.

MS. received, 6th November, 1920. Read, 13th January, 1921

When a parallel beam is incident normally on a glass-air surface the proportion that is reflected is $(n-1)^2/(n+1)^2$, i.e. approximately 5 per cent. The balance, viz. $4n/(n+1)^2$ is transmitted.

With a single parallel plate. The amount of incident light is taken to be 1, of which there is reflected at 1st surface $(n-1)^2/(n+1)^2 = \alpha$, say; transmitted $1-\alpha$, which reaches 2nd surface. Of this $\alpha(1-\alpha)$ is reflected and $(1-\alpha)^2$ transmitted. The amount $\alpha(1-\alpha)$ which is reflected back from the 2nd surface reaches the 1st one and of this amount $\alpha^2(1-\alpha)$ is reflected back once more and $\alpha(1-\alpha)^2$ passes out and is lost. Hence $\alpha^2(1-\alpha)^2$ gets through the plate in the required direction and $\alpha^2(1-\alpha)$ is reflected back. It follows that the total amount which emerges is $(1-\alpha)^2+\alpha^2(1-\alpha)^2+\alpha^4(1-\alpha)^2+\ldots$ to inf.

$$=\frac{(1-\alpha)^2}{1-\alpha^2}=\frac{1-\alpha}{1+\alpha}.$$

The amount reflected is $\dfrac{2\alpha}{1+\alpha}$.

N parallel plates. Let $f(N)$ be the total amount which passes through N plates so that $1-f(N)$ is the amount reflected back. Add one additional plate.

$f(N)\dfrac{1-\alpha}{1+\alpha}$ passes through this $(N+1)$th plate,

$f(N)\dfrac{2\alpha}{1+\alpha}$ is reflected back,

Of the latter

$\{f(N)\}^2\dfrac{2\alpha}{1+\alpha}$ passes through the N plates and is lost,

and $f(N)\{1-f(N)\}\dfrac{2\alpha}{1+\alpha}\dfrac{1-\alpha}{1+\alpha}$ passes through the $(N+1)$th plate,

while $f(N)\{1-f(N)\}\left(\dfrac{2\alpha}{1+\alpha}\right)^2$ is reflected back.

Again of this amount

$\{f(N)\}^2\{1-f(N)\}\left(\frac{2\alpha}{1+\alpha}\right)^2$ passes through the N plates and is lost:

$\{f(N)\}\{1-f(N)\}^2\left(\frac{2\alpha}{1+\alpha}\right)^2$ is reflected back,

and $\{f(N)\}\{1-f(N)\}^2\left(\frac{2\alpha}{1+\alpha}\right)^2\frac{1-\alpha}{1+\alpha}$ passes through the $(N+1)$th plate,

while $\{f(N)\}\{1-f(N)\}^2\left(\frac{2\alpha}{1+\alpha}\right)^3$ is reflected back.

Hence the total emergent beam is

$$f(N+1)=f(N)\frac{1-\alpha}{1+\alpha}+f(N)\{1-f(N)\}\frac{2\alpha}{1+\alpha}\frac{1-\alpha}{1+\alpha}$$
$$+f(N)\{1-f(N)\}^2\left(\frac{2\alpha}{1+\alpha}\right)^2\frac{1-\alpha}{1+\alpha}+\ldots \text{ etc.}$$
$$=f(N)\frac{1-\alpha}{1+\alpha}\left[1+\{1-f(N)\}\frac{2\alpha}{1+\alpha}+\{1-f(N)\}^2\left(\frac{2\alpha}{1+\alpha}\right)^2+\ldots\right]$$
$$=f(N)\frac{1-\alpha}{1+\alpha}\left[\frac{1}{1-\frac{2\alpha}{1+\alpha}\{1-f(N)\}}\right]$$
$$=\frac{f(N)}{1+\frac{2\alpha}{1-\alpha}f(N)}.$$

Hence

$$\begin{aligned}
1/f(N+1)-1/f(N) &= 2\alpha/(1-\alpha)\\
1/f(N)\quad -1/f(N-1) &= 2\alpha/(1-\alpha)\\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots &= \ldots\ldots\ldots\\
1/f(2)\quad -1/f(1) &= 2\alpha/(1-\alpha)\\
1/f(1) &= (1+\alpha)/(1-\alpha).
\end{aligned}$$

Omitting the first of these equations and adding

$$1/f(N)=(N-1)\,2\alpha/(1-\alpha)+(1+\alpha)/(1-\alpha)=1+2N\alpha/(1-\alpha)$$

or
$$f(N)=\frac{1-\alpha}{1+(2N-1)\,\alpha}.$$

If
$$\alpha = 5 \text{ per cent.}$$
$$f(N)=\frac{19}{19+2N}.$$

With 10 plates $f(10)=\frac{19}{19+20}=48{\cdot}8$ per cent.

With 20 plates $f(20)=\frac{19}{19+40}=32{\cdot}2$ per cent.

If instead of a pile of parallel plates there is a series of lens surfaces the matter is rather more complicated because (i) the light will not be all normally incident on the surface, and (ii) owing to the curvatures of the surface any light which is not transmitted straight through but undergoes internal reflections will be out of focus. As regards (i) the proportion of light reflected increases as a departure is made from the normal, but up to 45° this increase only amounts to about 1 per cent. and can reasonably be neglected.

If N is the number of lenses the amount of light which goes through without any internal reflection is $(1-\alpha)^{2N}$ and therefore there is an additional amount equal to $\frac{1-\alpha}{1+(2N-1)\alpha} - (1-\alpha)^{2N}$ which goes through and which is out of focus. In a periscope, for instance, with 10 lenses the amount is 48·8 per cent. by the parallel plate formula and 35·8 per cent. of this has come through without internal reflection. On the top therefore of 35·8 per cent. of light which is in focus there is an additional 13 per cent. which is out of focus. With 20 lenses there is 12·9 per cent. in focus, 19·3 per cent. out of focus, that is to say in such an instrument more than half the light which reaches the eye is of no use for purpose of seeing the object under observation. The figures given above must not be looked upon as being anything like practically exact. No consideration has been given to the loss by absorption in the glass itself or the changes in α that will occur when the lenses have different refractive indices. Neither has it been definitely established that there is not some slight surface absorption. Such will certainly be the case if the surface is not perfectly clean and it may be taken for granted that in an instrument in practical use the amount of transmitted light will be distinctly less than the figures given above. It is thought, however, that they do possess an interest as a rough comparison of the proportions of "in focus" and "out of focus" transmitted light.

EXHIBIT OF THE BRITANNIC HOMOGENEOUS-PRISM BINOCULAR

By J. H. BARTON
(Messrs BARTON LINNARD, Ltd.)

(Communicated by Wm. Shackleton)

Exhibited, 13th January, 1921

In this binocular, which was designed by the author, the object has been to obtain a greater amount of illumination by using a triple prism system in each body. As the prisms are cemented together, there are fewer air-glass surfaces than in the ordinary dual prism system, and the gain in light is very appreciable. A similar prism system is employed in some binoculars by other makers, but the prisms are placed in circular boxes immediately under the eyepieces and such instruments are of necessity cumbersome. In this new instrument the prisms are situated immediately over the objectives *in the bodies* of the instrument and the bodies have been specially designed to be neat and attractive in appearance and at the same time to hold the prism system securely so that the adjustments may be readily made and the alignment be permanent.

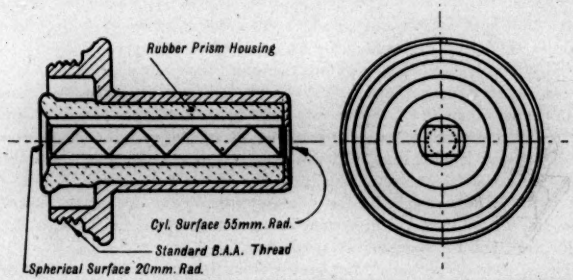
The mechanical portions differ greatly from the ordinary type and consist of a centre block piece on which are mounted rigid steel arms projecting right and left from the block piece. The bodies are mounted on these arms and a milled head enables the interocular distance to be readily attained, the bodies being moved symmetrically outwards or inwards.

EXHIBIT OF A DIRECT VISION STAR SPECTROSCOPE

By L. W. C. SMITH

Exhibited, 13th January, 1921

In the prism of this instrument a departure is made from the usual practice of using light crown and very dense flint glasses. These are replaced by dense barium crown ($n_D = 1{\cdot}6106$, $\nu = 58{\cdot}9$) and medium dense flint ($n_D = 1{\cdot}6114$, $\nu = 37{\cdot}1$) glasses of equal refractive index for the part of the spectrum for which the prism is to give direct vision. The selected ray (for this spectroscope the D ray) passes undeviated along the axis, and, as the prism consists of four flint and five crown components cemented together, the other rays are deviated by nine small increments on either side of the axis. The construction allows a spherical surface to be worked on the front face of the prism, for focussing on the star image, and a



cylindrical surface on the back face, for broadening the spectrum. The glass-air surfaces are thus reduced to the absolute minimum, and the strong internal reflections and violet absorption of the usual direct vision prism are avoided. With a 3 inch telescope the eye point of the spherical surface is approximately 7 mm. behind the back surface of the prism. The useful angular field is about 6° and the angular dispersion ($A - H$) is 7° 50′. Assuming that ·945 of the light is transmitted at each of the two glass-air surfaces, ·9992 at each of the 16 balsam-glass surfaces, and ·01 is absorbed by 1 cm. thickness of glass, the percentage of light transmitted $= (\cdot 945)^2 \times (\cdot 9992)^{16} \times (\cdot 99)^{4 \cdot 5} = 84{\cdot}3$ approximately, since the total thickness of glass = 4·5 cms. In practice the gain in light efficiency is very fully realised. When used with telescope object glasses of $F/15$ aperture the chromatic and spherical aberrations of the spherical surface are not troublesome. With $F/6$ to $F/8$ reflecting telescopes it is desirable to replace the spherical surface by an achromatic doublet placed in the usual way with its flat surface towards the image.

EXHIBIT OF A STUDENTS' OPTICAL BENCH

By Prof. F. J. CHESHIRE, C.B.E., F.Inst.P.

Exhibited, 13th January, 1921

This bench which has been designed more particularly to meet the laboratory requirements of elementary students of optics, is made up, as far as possible, of components which are already being made in large quantities, and therefore cheaply, for other purposes. The bench proper is a Chesterman steel rule, one metre long, and graduated either in millimetres or tenths of an inch*. This rule is clamped to a wooden base-board, either (1) vertically, or (2) tilted backwards at an angle of about 45°. For simple lens work the latter position is very convenient, enabling the student to work and to read the scale whilst in a comfortable sitting position.

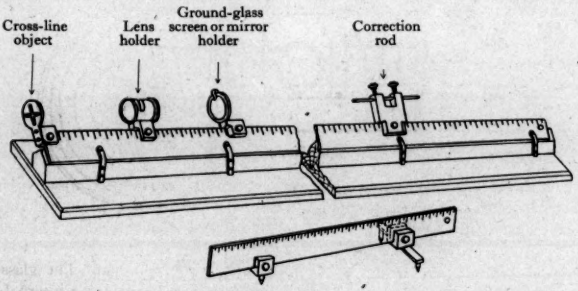


Fig. 1

The lenses employed are taken from an ordinary optician's trial case. Two sizes of these lenses, unfortunately, are on the English market, the first, of English make, with a diameter of 1½ inches (38 mm.), and those of French make with a diameter of 37 mm. The lenses of both makes can be obtained either edged but unmounted, or mounted in a metal rim with a finger holding-tab. The unmounted lenses can be mounted on the bench more easily, but they get very dirty in laboratory use, so that the mounted lenses with metal tabs are recommended. Fig. 1 shows a one-metre bench inclined backwards as described, and carrying a number of typical fittings. In front of this bench a second one, a foot in length, is shown fitted up as an experimental Galilean telescope.

* Rules 2 metres and 1·5 metres long may also be obtained from Messrs Chesterman.

The lens holder, as shown by Fig. 2, consists of a short length of tube *A*, with an internal diameter equal to that of the lens employed, which is sweated to a block *B* slotted longitudinally at *C* to engage with the metre rule, upon which it is secured in position by a clamping screw *D*. The lens is slipped laterally into the tube *A* through the opening *E*, and then pushed up against an end annular stop by a short sliding tube *F*. The scale is read at the bevelled edge *G*. Sliding fittings are also provided for carrying perforated objects, cross wires, reflectors for auto-collimation work, measuring rods, ground glass screens, etc. Most of these, however, can alternatively be made up in the form of discs which can be secured in

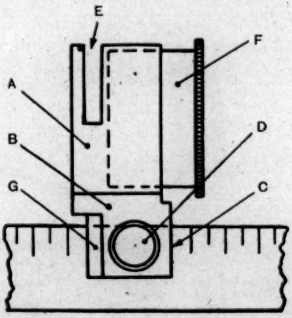


Fig. 2

the lens fitting described above. The various fittings can be used upon rules of different lengths, as an ordinary engineer's foot rule, for example. Models of various optical instruments can thus be set up, used, and experimented with. The optical bench can also be very conveniently mounted in front of a lantern and used for lecture projection work. In this work, however, it is desirable that the lens which projects the final picture upon the screen should be achromatic. Such lenses are also useful for making up models of achromatic instruments, as telescopes, etc.

This bench has been in continual use in the Optical Department of the Imperial College since its creation, and has been found to be capable of many applications and to be very satisfactory in use.

EXHIBIT OF A NEW ERECTING EYEPIECE

By Dr R. A. HOUSTOUN
(Communicated by J. S. Anderson)

Exhibited, 13th January, 1921

The astronomical telescope, while giving a much larger field than the Galilean telescope, has the disadvantage for terrestrial use that it inverts the image. This disadvantage is usually remedied either by prisms, as in the prismatic binoculars, or by an erecting eyepiece employing four lenses. The present note describes how by a slight modification the ordinary Ramsden eyepiece may be made to serve as an erecting eyepiece.

The Ramsden eyepiece consists of two equal plano-convex lenses with their curved faces turned towards one another and the distance between them equal to two-thirds of the focal length of either. Separate them so that their distance becomes equal to their focal length, and silver the upper half of the field lens and

lower half of the eye lens. Let A be the ordinary inverted image formed by the object glass. The silvered half of the eye lens forms a real erect image of this at B; this is viewed by the unsilvered half of the eyepiece, and is seen as a virtual erect image at infinity. At the same time the silvered half of the field lens acts as condenser, and ensures that all the light falling on the silvered half of the eye lens passes through the unsilvered half.

With the arrangement shown in the diagram the erect image is seen above the inverted one. If, however, the lower half of the field lens is cut away, only the erect image is seen. The field is then, of course, semi-circular in shape. With a small field the definition of the erect image is quite as good as that of the ordinary inverted one. With a large field of 40° diameter, however, I have not yet been able to obtain definition at all comparable with that given by the eyepiece used in prism glasses.

REVIEW

Penrose's Annual: The Process Year Book. Edited by WILLIAM GAMBLE, F.R.P.S., F.O.S., Vol. 23. Pp. xii + 88. (Bradford: Percy Lund, Humphries & Co., Ltd., 1921.) Price 10s. 6*d.* net.

This volume is a worthy successor to the Victory Volume published last year. It contains over twenty interesting articles on various subjects directly or indirectly connected with process work. "The Airbrush in Photography," "High-Light Processes in Photo-Lithography," "A New Sensitizing Method with Bichromate," "A Suggestion for a New Method of Photography in Colour," and "Wet and Dry Colour Plates" may serve as examples of the kinds of articles provided. The book contains a large collection of prints illustrating process work during the year 1920. Many of the coloured prints are specially worthy of admiration. The high standard of work represented in this volume serves as a very good advertisement to Messrs Penrose. The book should have a large sale, for it is not merely an advertisement, but also a work of art.

J. S. A.

ABSTRACTS

Experimental Researches and Reports, published by the Department of Glass Technology, The University, Sheffield, Vol. II (1918–19).

This volume contains a number of reprints of papers which Dr W. E. S. Turner and his colleagues have contributed to the *Journal of the Society of Glass Technology*. The papers deal with a variety of subjects connected with the manufacture of glass, as, for example, the properties and annealing temperatures of lime-soda and magnesia-soda glasses, investigations on chemical glassware, experiments on glass for lamp-working purposes, and apparatus for the calibration of burette tubes and for the detection of strain in glass. In addition, there are more general articles on bottle-glass and bottle-glass manufacture, the glass industry of North America, and the year's progress in glass research under the auspices of the Glass Research Delegacy. The volume, which is full of results of great importance to the glass industry, forms a useful record of the research activities of Dr Turner's department.

J. S. A.

"The Effect of Strain on the Properties of Optical Glass." By G. BERNDT, *Z. f. Instrk.* 40 (1920), 20, 37, 56, 70.

The author investigates the problem of how the properties of optical glass are influenced by strain due to imperfect annealing. Results are given of measurements on a specimen of mirror glass and a specimen of borosilicate crown 516/640 made by the Sendlinger Optischen Glaswerke G. m. b. H. of Zehlendorf, Berlin.

The results obtained are as follows:

	Mirror glass		Borosilicate Crown	
Compressive strength	12,400–13,800	kilos/cm.²	18,100–20,900	kilos/cm.²
Breaking strength	710–760	,,	690–870	,,
Bending strength	920–980	,,	1,080–1,120	,,
Hardness			55·3	
Modulus of elasticity			814,600	,,

The first number denotes the mean value and the second number the maximum value. If the outer compressed layer of glass is left, the breaking strength is greater in strained than in annealed glass; if, however, the compressed layer is removed, so that the outer layer is in a state of tension, the opposite is the case. The hardness is not affected by strain. The effect of great strain in worked pieces of glass is to decrease the density by ·8 per cent. and the refractive index by 2·2 per cent. The specific refractivity $\frac{n^2-1}{d}$ remains constant to about $\frac{1}{10}$ per cent. The same relations hold for the coefficient of expansion as have been mentioned in the case of the breaking strength. The forces due to strain amount to about 2000 kilos/cm.^{2}, which corresponds to a shortening of about ·3 mm. in a length of 100 mm. Hooke's law holds with great accuracy in the case of glass almost up to the breaking point. The experiments thus show that observations of glass constants should only be made with carefully annealed specimens, since otherwise in the determination of compressive strength, elasticity modulus, and coefficient of expansion differences up to 15 per cent. may easily be obtained. Strain may affect the value of the density to about two units in the second decimal place and the value of the refractive index to three units in the third decimal place. The paper contains tables of all the results obtained for both strained and annealed specimens.

J. S. A.

"Photographic Objectives." By H. SCHMIDT, *Central-Zeitung f. Opt. u. Mech.* 41 (1920), 297.

The author gives a list of all the known kinds of German camera lenses, classified according to type. In each case the aperture ratio and the angular field of view are given.

J. S. A.

"Axial Caustics in Systems corrected for Spherical Aberration." By M. BEREK and A. DRIESEN, *Central-Zeitung f. Opt. u. Mech.* 41 (1920), 325.

The value of the aperture of an objective, for which the longitudinal spherical aberration is zero, is called the "corrected aperture." Denoting this by M, the author shows, by developing the equation of the axial caustic, that when the aperture is increased from $\frac{\sqrt{5}+1}{2\sqrt{5}}M$ to $\frac{2}{\sqrt{5}}M$ the position of the smallest cross-section of the bundle of rays remains at a distance of $\frac{4}{5}X$ from the axial apex of the caustic, the radius of the circle of least confusion being $\frac{8}{25}\sqrt{\frac{1}{5}}XM$, where X is the zonal error of the objective. If the aperture is increased beyond $\frac{2}{\sqrt{5}}M$, the plane of smallest cross-section moves away from the axial apex of the caustic and the lateral spherical aberration in that plane increases rapidly. There is reason, therefore, for the practice of keeping the effective aperture of an objective smaller than the aperture M for which it is corrected as regards spherical aberration.

J. S. A.

"Graphical Methods of finding Axial Conjugate Points." By Dr H. ERFLE, *Central-Zeitung f. Opt. u. Mech.* 41 (1920), 351, 366.

The author draws attention to the fact that the method described by Dr A. Kühl (see Abstract in *Trans. Opt. Soc.* 21 (1919–20), 222) is not new, and gives a resumé of the different graphical methods that have already been published. The paper includes descriptions of suggested simplifications and generalisations of some of these methods and also a complete bibliography of the subject.

J. S. A.

NOTICES

THE eleventh annual Exhibition of Electrical, Optical, and other Physical Apparatus was held by the Physical Society of London and the Optical Society at the Imperial College of Science and Technology on the 5th and 6th of January, 1921.

THE INSTITUTE OF PHYSICS

EXAMINATIONS FOR ASSOCIATESHIP, 1921

NOTICE is hereby given that the Institute will hold its first Examination of Candidates for the Associateship, in London, at the latter end of September, 1921.

Applications for entry must be received before June 15th, 1921. Forms of application can be had from the Secretary, 10, Essex Street, London, W.C. 2.

The Institute is now prepared to register Students. Registration Forms will be sent on application.

By order of the Board,

F. S. SPIERS, Secretary